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THE MAPPING OF LAKE SURFACE WATER CHARACTERISTICS OF NORTHEASTERN ONTARIO USING SATELLITE IMAGERY

RAC Project No. 354 G

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RAC Project No. 354 G

Report prepared for:
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Summary

Throughout the world, a great deal of effort is being directed towards the development of water quality monitoring techniques based on remotely sensed data. This report describes associations between lake water parameters in Northeastern Ontario and reflectance data acquired by satellite sensors, the Landsat Multispectral Scanner (MSS) and the Thematic Mapper (TM). Focussing on lake acidity and trophic status relationships, it is the most extensive application of its kind ever undertaken in Canada, with virtually every lake examined in an area that exceeds 120,000 km^2.

Two hundred and thirty lakes were used to calibrate relationships between Landsat TM radiance measurements and close to 30 water chemistry parameters collected from field surveys designed especially for this project or included in databases of the Ontario Ministries of the Environment and Natural Resources.

In one set of procedures, the sample lakes were classified on the basis of common water chemistry variables using the numerical taxonomic techniques of principal components, cluster, and discriminant analyses. Whereas classification accuracies of 90% or more could be achieved

using lake survey data itself, the same lake classes could be replicated at a level of accuracy of only 70% using Landsat TM data alone. Despite this lower level of classification, Landsat data readily permitted the discrimination between lakes of low colour - high transparency - low nutrient status, compared to lakes with high colour - low transparency - high nutrient status.

The approach to developing associations between Landsat data and lake water parameters was further refined by generating regression models which would allow for the predictions of dissolved organic carbon concentrations (DOC). The regression models that were derived are being used to map lake DOC concentrations using five mapping classes: 0.0 - 2.0, 2.1 - 4.0, 4.1 - 6.0, 6.1 - 8.0, and > 8.0 $mg.L^{-1}$.

Within the principal survey area (extending approximately from lakes Nipissing and Temiskiming to Lake Superior, and from the North Channel of Georgian Bay to Highway 11 between Hearst and Cochrane), 90% of the project lakes could be predicted to within ± 1 DOC mapping category, with 60% or more of the lakes falling within the same observed/predicted DOC category. Varying somewhat by region, the mean absolute differences between observed and predicted DOC ranged from 0.62 to 0.98 $mg.L^{-1}$. Landsat

predictions of DOC for more than 70% of the study lakes were within ± 1.0 $mg.L^{-1}$ of the DOC values gathered from field surveys, while 90% were within ± 2.0 $mg.L^{-1}$.

The regression models were then applied in the form of a "blind test" to lakes in the area extending from south of Lake Nipissing and to just north of the community of Dorset. The models tended to over-predict the DOC concentrations in this area (based on 17 lakes), with a mean absolute difference between observed and predicted DOC of 1.11 $mg.L^{-1}$. Even so, the predictions for more than 80% of this smaller set of lakes were within ± 2.0 $mg.L^{-1}$ of observed DOC concentrations.

As a final component of this study, work was initiated on the use of Landsat data (both TM and MSS) as a temporal water quality monitoring tool. In this part of the study only one lake was examined - Bowland Lake, located 70 km north of Sudbury - using satellite data from seven different years from 1973 to 1986. Landsat reflectance ratios for Bowland suggest, but at this time do not confirm, that optical changes associated with lake neutralization can be detected. Preliminary results do suggest that satellite data may enable the detection of even subtle changes in the optical properties of inland lakes and would therefore provide some capability for monitoring change through time.

If Landsat data can be used to predict DOC with reasonable accuracy and if DOC can be used as a surrogate measure of other lake parameters, then Landsat and other remotely sensed data should be used as a water quality monitoring tool. The results of this research project, undertaken in an area of the province where Landsat/DOC relationships can be linked to lake acidity and trophic status, strongly support this proposition. Certainly as a reconnaissance tool, at the very least, satellite data could be used to guide the sampling programs of more intensive *in situ* surveys. In regions where lakes are numerous, remote in location, and scattered over an enormous geographical area, remately sensed data will provide spatial and likely temporal information for a set of study lakes that is impossible to acquire in any other manner.

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1. Introduction

1.1 Project Scope and Objectives

Is it possible to use remotely sensed data to, in some manner, determine the trophic state of lakes in Northeastern Ontario? Is it possible to use remotely sensed data to assess the spatial extent of lake acidification in Northeastern Ontario? Is it possible to use remotely sensed data to detect the water quality changes in the lakes of the region that have been observed from synoptic surveys?

These are the principal questions that are addressed in this study, noting that: there is an emphasis on addressing questions concerning lake acidification; and with the qualification that, the terms "remotely sensed data" and "remote sensing" refer primarily to satellite imagery. If any or all of the questions can be answered in the affirmative, then remote sensing will be a useful addition to the tools that can be used to provide for the monitoring of lakes here and possibly throughout the Province of Ontario.

In regions where lakes are numerous, remote in location, and scattered over an enormous geographical area, routine or even special-purpose limnological surveys pose

considerable challenge and expense. Remote sensing offers a potential capability of gathering at least some of the surface water parameters that are required in a relatively rapid, efficient, and economical manner. Undertaken prior to standard lake survey methods, remote sensing results may then be used to guide the sampling programs of more intensive *in situ* surveys. They may also provide spatial and temporal information for a set of study lakes that is impossible to acquire in any other manner.

Northeastern Ontario provides a unique opportunity to test these proposals. Located in this area is the world's largest, single point-source of sulphur dioxide emissions, the Sudbury nickel-copper smelting complexes of the Inco Metals Company and Falconbridge Nickel Mines Limited. The adverse effects of acidic deposition on the freshwater systems of the region is a major environmental concern that has long been recognized (Gorham and Gordon 1960; Beamish and Harvey 1972). Of equal concern, but still contentious due to the lack of well-documented studies are the real or inferred costs of acid rain associated with impacts on human health and damage to the tourism and forestry industries of the area (Weller 1980; Sub-committee on Acid Rain 1981).

Over the past decade and a half, major changes in smelting processes, the adoption of pollution abatement

measures, an extended strike, and numerous shutdown periods have substantially reduced airborne emissions in the Sudbury area. For example, estimated annual SO_2 emissions ranged from 3,663 to 6,383 tonne day^{-1} over the period 1970-1977 compared to the range of 1,065 to 2,562 tonne day^{-1} during 1978-1983 (Ontario/Canada Task Force 1982; M.O.E. 1986). Substantial reductions and altered deposition patterns have also been reported on a province-wide basis (Kelso and Jeffries 1988).

Associated with these reduced emissions, lake water quality improvements have been observed in the Sudbury area, including: increases in pH and alkalinity; and decreases in sulphate, nickel, and copper concentrations (Keller and Pitblado 1986; Keller et al. 1986). It is hypothesized that some of the changes that have occurred within these lakes can be detected by image analysis techniques.

Tentative, yet affirmative answers to the questions posed at the beginning of this section were provided in the feasibility study (Pitblado 1987a) undertaken in preparation for the present project. However, that first project only dealt with lakes confined to two relatively small areas: a region of 750 km^2 in the Sudbury area, north of Lake Wanapitei; and a region of 525 km^2 north of Sault Ste. Marie in the Montreal River area. This report outlines efforts to

extend the initial findings of the feasibility study to a much broader area of Northeastern Ontario.

The immediate aim of this project was to characterize, map or classify the lakes (in terms of general trophic state as well as discriminating between acidified and non-acidified lakes) of a major portion of the Northeastern Region (M.O.E.), plus two smaller regions in northwestern and southern Ontario, using reflectance data from the Landsat Thematic Mapper satellite sensor. This report focuses on the northeastern and southern Ontario regions as the northwestern study area (centred on Quetico Provincial Park) has been featured in a thesis by Savard (1990). In the course of this work, an opportunity arose which allowed for the examination of spectral responses over time (1973 to 1986) for an acidic lake (Bowland) in northeastern Ontario that had been neutralized in 1983. The results of both the spatial and temporal studies are provided in this report. In the long-term, the goal of these projects is to provide a basis for employing remote sensing as an aid in the monitoring of inland lake water quality in the Province of Ontario.

1.2 Water Quality Assessment And Remote Sensing

> "Very few investigators claim to have an operational water quality measurement technique. The truly efficient techniques that are satellite-based are even fewer because they tax the technology to its limits." (Alföldi 1982).

Before examining Alföldi's statement, it is necessary to outline some of the characteristics (for additional details see, Swain and Davis 1978; Richards 1986; C.C.R.S. 1991) of the satellites and satellite data that are used in this report.

In 1972 the United States National Aeronautics and Space Administration (NASA) launched the first in a series of satellites in their Earth Resources Technology Satellite (ERTS) programme, subsequently named **Landsat**. With virtually the same instrumentation as this first satellite, Landsat 2 and Landsat 3 were successfully put into orbit in 1975 and 1978, respectively. In 1982 and 1984, the next two satellites in the series, Landsats 4 and 5, were launched but with significantly improved sensors. It is anticipated that Landsat 6 will be operational by 1992. At present, data are only being received on a regular basis from Landsat 5 and only occasionally from Landsat 4, while Landsats 1 to 3 have been shut down.

These satellites have been placed in repetitive, circular, near-polar, sun-synchronous orbits at nominal altitudes of 920 km (Landsats 1 to 3) or 705 km (Landsats 4 and 5). With orbital times of from 103 to 98.9 minutes, 14 orbits of the earth could be completed each day. Given the earth's rotation, successive orbits would follow different ground tracks, such that measurements of most places on the earth would occur every 18 (Landsats 1-3) to 16 days (Landsats 4-5). This repetitive coverage is considered to be one of the great advantages of satellite resources monitoring. Unfortunately, the scanning instruments on board are unable to penetrate cloud; thus, the increase in **temporal resolution** of from 18- to 16-day repetitive coverage advantage is only theoretical.

Using oscillating mirror scanning systems and a series of photosensitive detectors allows the Landsat satellites to obtain readings from the ground surface over an 185 km-wide swath along the orbital tracks of the satellites. The smallest area on the ground for which measurements can be made is called a **pixel**, short for 'picture element'. An MSS pixel covers an area that is 79 m by 57 m, approximately 0.5 hectares. For TM, the pixel size is 30 m by 30 m (0.1 ha). This smaller-sized pixel for TM provides for greater **spatial resolution**. The overall ground area covered by a standard Landsat scene is 185 km (across swath) by from 160 to 185 km

(along satellite track), depending on how receiving stations frame the continuous receipt of satellite data.

Of the various instruments on board these satellites, the most important for environmental monitoring have proved to be the Multispectral Scanner (MSS) and the Thematic Mapper (TM). Both of the scanning instruments are carried by Landsats 4 and 5, while Landsats 1 to 3 only carried the MSS. These scanners measure the earth's reflected radiation in specific and relatively narrow bands of the electromagnetic spectrum. In addition, TM is capable of sensing heat, or emitted thermal radiation. There is a significant increase in **radiometric resolution** for the Thematic Mapper over the Multispectral Scanner. In general, the detectors used by Landsats 1-3 allowed for measurements to be scaled over a range of digital numbers (DNs) from 0 to 63 while Landsats 4-5 DN values range from 0 to 255.

The wavelength bounds of the Landsat sensor bands or channels are listed in Table 1.1. Note that there are only four channels for MSS but seven for TM. This improvement from four to seven channels is referred to as an increase in **spectral resolution**.

Table 1.1 Landsat spectral bandwidths (wavelength bounds expressed in μm)

Multispectral Scanner (Landsat 1, 2, 3, 4, 5)		Thematic Mapper (Landsat 4, 5)	
Band No.	Channel Wavelengths	Band No.	Channel Wavelengths
1	0.5-0.6 (green/yellow)	1	0.45-0.52 (blue)
2	0.6-0.7 (red)	2	0.52-0.60 (green/yellow)
3	0.7-0.8 (near infrared)	3	0.63-0.69 (red)
4	0.8-1.1 (near infrared)	4	0.76-0.90 (near infrared)
		5	1.55-1.75 (mid-infrared)
		6	10.4-12.5 (thermal IR)
		7	2.08-2.35 (mid-infrared)

Returning now to Alföldi's comments that were quoted at the beginning of this section, it is critical to note that he was writing prior to the use of the Thematic Mapper with the launch of Landsat 4. Up to that point in time and continuing, digital data from the Multispectral Scanner of the Landsat series of satellites have been employed since the launch of Landsat 1 for a wide range of lake water quality assessment programs (Brooks 1975; Alföldi and Munday 1977, 1978; Fisher et al. 1979; Scarpace et al. 1979; Lillesand et al. 1983; Verdin, 1985; and other citations provided in the References in this report). These activities have only been partially successful due to the

relatively coarse resolutions of MSS data (Middleton and Munday, Jr. 1980; Witzig and Whitehurst 1981; Hilton 1984; Pitblado 1984; Lindell 1986). It should also be pointed out that **Landsat** was originally designed with terrestrial targets in mind. This is the case for both MSS and TM, but the addition of the blue band on the Thematic Mapper is a boon for studies of aquatic targets.

Alföldi (1982) and others (see for example, Lathrop and Lillesand 1986; Lindell et al. 1986) predicted and are now demonstrating that the resolution improvements (temporal, radiometric, spatial, and spectral) of the Thematic Mapper would and do enhance satellite water quality assessments. Even so, if the most recent review (Hockey et al. 1990) of applications of remote sensing in the field of water resources assessment is truly representative, remote sensing still does not have widespread operational status as a water quality measurement tool. This situation persists, in spite of the numerous reports of successful applications reported in the remote sensing literature.

Prior to the present work which was initiated in 1986, only two attempts had been made at using remotely sensed data for the analyses of water quality in Northeastern Ontario. In one, the Landsat chromaticity indices of Alföldi and Munday, Jr. (see, for example: Munday, Jr. and

Alföldi 1975; Alföldi and Munday, Jr. 1977 and 1978) were applied to aerial photographs to detect water quality changes in acid-stressed lakes in the Killarney Provincial Park (Hardy and Jeffries 1981). In the second, Moniteq (1982) attempted to assess the feasibility of using digital Landsat data to match lake water reflectance with lake acidity for selected lakes north of the City of Sudbury.

Hardy and Jeffries (1981) argued that chromaticity coefficients were highly correlated with chlorophyll content in the surface waters of Killarney lakes; and in turn, chlorophyll content was highly correlated with lake acidity as measured by pH. The response to the Hardy and Jeffries paper was very negative (Pitblado 1984). In a review article, Bukata et al. (1982) concluded, "There may well be remote sensing techniques capable of reliable estimations of the acidic status of a natural water mass. However, the methodology suggested by the Hardy and Jeffries work is not one of them". The Moniteq (1982) effort was much more useful but failed to exploit the available digital satellite and field limnological data (Pitblado 1984).

While difficulties have been encountered, it is felt that significant advances in satellite-based water quality monitoring have been made through this M.O.E.-funded project. Many of the steps that have been undertaken have

already been presented (Marshall and Tanis 1989; Pitblado 1984, 1986, 1987a, 1987b, 1991; Pitblado and Dempsey 1989; Pitblado et al. 1987, 1990) and are further documented in this report.

1.3 Lake Trophic Status

> "It is not always easy to place a lake in a definite class. Some seem to be mosaics of what we assume to be eutrophic as well as oligotrophic" (Cole 1979, p. 17)
>
> "In nature there are only smooth and continuous transitions between various lake types" (Hakanson 1984, p. 313)

Textbook lake typology may often lead one to believe that it is a simple matter to place a lake in a class or taxa, however defined. One might adopt a classification scheme using the familiar terms associated with eutrophication, contrasting oligotrophic with eutrophic lakes. The former are characterized as: deep, steep-banked, with epilimnion volume relatively small compared with hypolimnion, blue to green water colours, marked transparency, with water poor in plant nutrients and Ca^{++}; while the latter are: shallow, with broad littoral zone, an epilimnion to hypolimnion ratio greater than the former class, green to yellow or brownish green in colour, limited transparency, and abundant plant nutrients and Ca^{++} (from Cole 1979 as modified from Thienemann 1925). And somewhere in between these contrasting trophic states we would find the class of mesotrophic lakes.

But it is evident from the quotations provided above

and a careful reading of limnology texts and journal articles that such simple discriminations of lake typology are not always made easily. While the general descriptions of lake trophic status are widely held, there is no common agreement on the details of allocating a lake to one or another of the trophic classes. Many authors attempt to employ a single lake parameter (transparency, oxygen content, depth, plankton biomass, or phosphorous concentration, etc.) as the principal guide with which to highlight the distinctions between oligotrophic and eutrophic lakes. By so doing, they open themselves to severe criticism from their colleagues (see also: Hutchinson 1957 and 1973; N.A.S. 1969; Likens 1972; or Wetzel 1975).

Any lake trophic classification based on a single criterion is subject to extreme debate because of the complex inter-relationships that exist within aquatic ecosystems. The single parameter may be employed as a useful surrogate within a limited survey or analysis, but as these are expanded in terms of numbers of lakes or geographical extent there will be more exceptions than the rule.

For this project, a multivariate, statistical approach has been adopted whereby lakes are grouped on the basis of shared similarities in terms of surface water and

morphological parameters. This approach has been successfully employed in earlier studies of Northeastern Ontario lakes with respect to their nutrient status, metal contamination, acidification, and zooplankton relationships (Pitblado et al. 1980; Keller and Pitblado 1984, 1989). It is also similar to the multivariate derivation of water quality indices advocated for general use by Joung et al. (1979).

Nonetheless and in apparent contrast to the preceding statements, single-variable expressions for lake typology can be very useful and defended on the basis either or both practical and theoretical grounds. In this report a great deal of importance is placed on the use of dissolved organic carbon concentrations (see sections 4 and 5) and to a much more limited extent the "Carlson trophic state index for lakes" (Carlson 1977). The latter has been included because it has been employed elsewhere for Landsat water quality assessments (Shapiro 1975; Lillesand et al. 1983).

The Carlson trophic state index (TSI) is one of the many derivatives or reformulations of the Beer-Lambert and Lambert-Bouger laws or equations which are used to describe the vertical extinction of light in water (Wetzel 1975; Megard et al. 1980). Many of the reformulations are attempts to express relationships between lake water

transparency (measured using Secchi disc depth) and algae or phytoplankton biomass (often measured in the form of volumetric concentrations of chlorophyll *a*). The latter is frequently employed to measure or indicate the productivity of natural waters.

Using these laws as a theoretical base and data collected from a group of lakes in Minnesota, Carlson (1977) expressed his primary trophic state index as follows:

$$TSISD = 10 (6 - \ln SD / \ln 2)$$

Where: TSISD - is used to indicate that the index is based on Secchi disc depth; Carlson also generated alternative TSI equations based on total phosphorous ($\mu g.L^{-1}$) and chlorophyll *a* ($\mu g.L^{-1}$).

SD - Secchi depth (m)

Carlson scaled the TSISD (using the 6 and the 10 in the equation) such that the range would be from 0 to 100. By so doing, he considered that a doubling of algae biomass would produce an index in this range that would reflect that the doubling (e.g. from 15 to 30) of an index value would represent twice as much biomass.

Theoretical difficulties do exist with the trophic state index, some of which have been acknowledged by the

originator (Carlson 1980). A discussion of these may be found in Lorenzen (1980) and Megard et al. (1980). But most of the criticisms have been rejected by Carlson (1980) and to some extent Edmondson (1980). And certainly from a pragmatic perspective, a number of scientists (e.g. Shapiro 1975; Lillesand et al. 1983) have found TSI values to be of considerable utility in the trophic classification of lakes using Landsat data and for subsequent lake management.

1.4 Lake Acidification

> "Scientists estimate that, if 1980 levels of acid loadings remain constant or increase over the next 10 to 20 years, Ontario could lose much or all of the aquatic life in as many as 48,000 susceptible lakes unless effective abatement measures are taken"
> (M.O.E. 1980)

The Ontario Ministry of the Environment has been concerned about the acidification of lakes in the Province for at least two decades. Their concern has been expressed technically through the activities of the Sudbury Environmental Study (S.E.S) and the Acidic Precipitation in Ontario Study (A.P.I.O.S.). Their concern has also been voiced in a wide variety of other forms - communications using both the print and broadcast media; presentations in non-scientific, popular journals and magazines; litigation; etc.

It is both impossible and inappropriate here to attempt to summarize M.O.E. work or presentations with respect to the problem of acidic precipitation (for technical reviews see, for example: Dillon et al. 1978 and 1984; Jeffries et al. 1986; Neary and Dillon 1988; Neary et al. 1990). However, two points that are directly relevant to this research project must be made.

The first point has already been referred to: in the course of this work, an opportunity arose which allowed for the examination of spectral responses over time (1973 to 1986) for an acidic lake (Bowland) that had been neutralized in 1983. And it has also been shown that very significant improvements in lake water quality in the Sudbury area have been recorded over that same period of time. Thus, an ancillary objective of the current project developed - a temporal form of analysis as opposed to the original spatial analysis.

The second point deals more specifically with the changes in the optical characteristics of water bodies as a result of acidification processes. In particular, Almer et al. (1974), Yan (1983), Dillon et al. (1984), and Effler et al. (1985) have demonstrated alterations in transparency (Secchi disc depth) which accompany lake acidification and neutralization. Increases in transparency with acidification have been observed in association with a depletion of dissolved organic carbon (DOC), perhaps due to coagulation/adsorption by aluminum and subsequent losses from the water column (Effler et al. 1985). Water clarity has been identified as a parameter that is capable of being determined using satellite data (Brooks 1975; Alföldi and Munday, Jr. 1977). In this report, the DOC-water clarity and related water colour links are shown to be of

fundamental importance when undertaking water quality studies using remotely sensed data.

2. Data Sources and Analyses

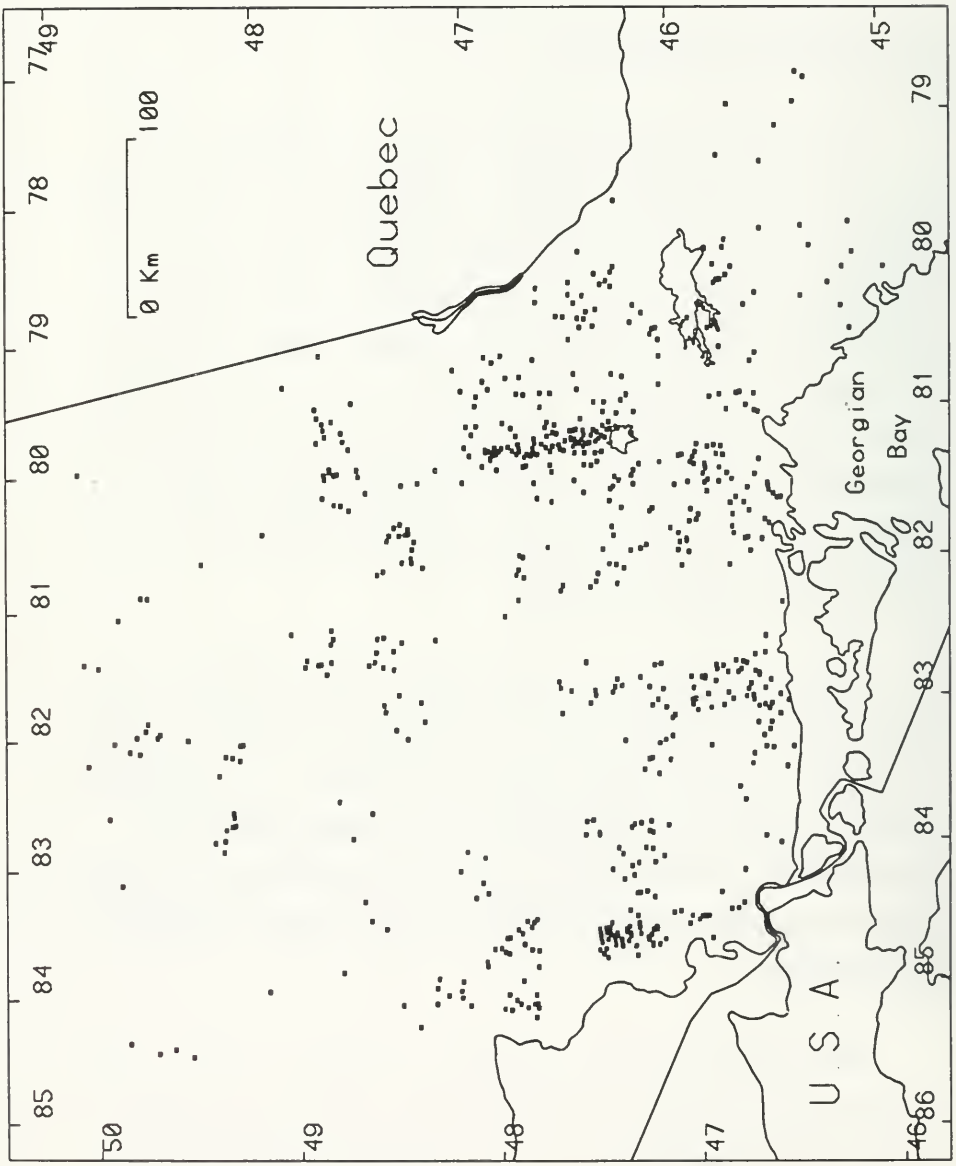
2.1 Extent of Study Area

The primary study area for this project spans the portion of northeastern Ontario from Highway 11 to the North Channel of Lake Huron (north-south) and from Wawa to the Temagami area (west-east). The secondary, southern study area extends from Lake Nipissing to just north of Dorset. The precise area has not been measured but is approximately 120,000 km^2 in extent. The boundaries of this relatively awkward-shaped study area were dictated by the availability of lake water chemistry and satellite imagery data, not by any jurisdictional definition.

A good impression of the extent of the study area can be garnered by examining the map (Figure 2.1) which locates the lakes for which field data were obtained. The schematic diagram (Figure 2.3) identifying the Landsat scenes that were employed reinforces that image and points out the gaps where no Landsat data were available during the progress of this project.

While these two maps (Figures 2.1 and 2.3) give a good view of the geographical extent of the entire study area, they leave an impression that an extremely large number of

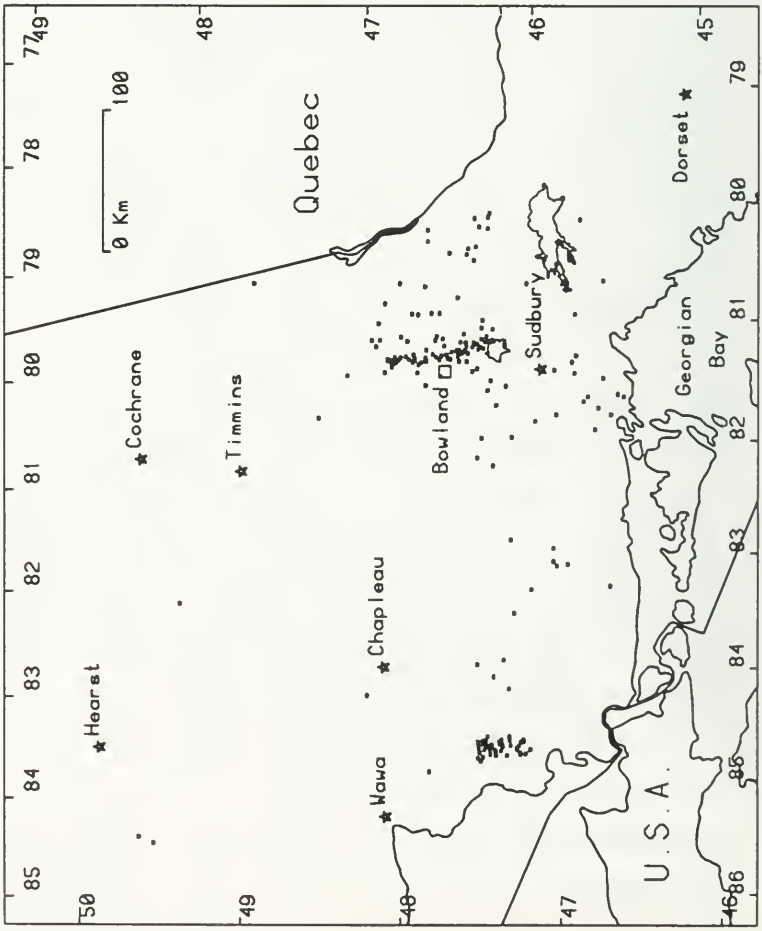
Figure 2.1 Location of study lakes for which some field data were available (n = 776).



lakes were available for deriving multivariate analyses of trophic conditions and water-reflectance associations. As indicated by the sections below, screening of these lakes was required leaving a primary dataset consisting of 230 lakes. The location of this latter group of lakes as well as the Bowland Lake site are shown in Figure 2.2.

Through the combination of the lakes distributed as shown in Figures 2.1 and 2.2, five of the seven sulphur deposition zones described by Neary et al. (1990) are represented. The majority of the study lakes are located in the two zones which dominate the geography of Notheastern Ontario. These include a broad swath from Lake Superior to the Lake Temiskaming (Zone 4) which overlaps the Sudbury area lakes (Zone 7). As provided by Neary et al. (1990), in 1973 the rates of sulphur deposition for these zones were 0.75-1.00 g $S.m^{-2}.yr^{-1}$ and >1.25 g $S.m^{-2}.yr^{-1}$ (essentially unknown), respectively. A relatively small number of lakes were available for analyses that represent the more northerly sulphur deposition areas of Zone 3 (0.50-0.75 g $S.m^{-2}.yr^{-1}$) and Zone 2 (0.25-0.50 g $S.m^{-2}.yr^{-1}$). Zone 5 (1.00-1.25 g $S.m^{-2}.yr^{-1}$) is located just north of the North Channel of Lake Huron and the entire area from Lake Nipissing southwards in Figures 2.1 and 2.2. Zone 5 was well represented by lakes but only for the northern section of that zone.

Figure 2.2 Location of primary study lakes - having sufficient field data for multivariate analyses of trophic conditions and the derivation of water-Landsat reflectance associations (n = 230). As illustrated, there are very few study lakes south of Lake Nipissing. This "Dorset" area is therefore a "blind" test area - where algorithms developed from more northerly areas are applied as a test.



2.2 Lake Chemistry Data

Essentially three surface water chemistry datasets were included in this study (the Bowland Lake information is outlined separately in a later section of the report). The first two were generated by the Ontario ministries of Environment and Natural Resources. M.O.E. data were drawn from the Aquatic Effects Programme (A.P.I.O.S.) database while M.N.R. data were derived from the database of the Aquatic Habitat Inventory Programme. Both of these datasets have been used and described numerous times by staff of the respective ministries, with the most recent summary of collection and analytical methodologies outlined by Neary et al. (1990). The third dataset, more fully described below, was generated as a result of the feasibility study undertaken prior to the present report (Pitblado 1987a).

Surface water parameters for approximately 4000 lake 'locations' were supplied to the author for this investigation. The number of usable lakes was reduced considerably by eliminating duplicate lakes (i.e. those lakes common to the three datasets) and those lakes that had been sampled outside the acceptable satellite imagery window - July/August. The 776 lakes shown in Figure 2.1 represent the study lakes that had at least some form of usable (in the context of this report) information. Depending on the

lake parameter being examined (see Table 3.1), however, only from 30 to 521 lakes were included in subsequent analyses.

The data as well as the collection and analytical methodologies for what has been referred to above as the third dataset have not been reported yet in an M.O.E. publication although they can be found in an unpublished document (Pitblado 1987a). To make that information more readily accessible these methodologies are outlined below and the water chemistry data listed in the Appendices D and E.

In August of 1986, two field areas were examined: a 75 km (north-south) by 10 km (east-west) region north from Lake Wanapitei in the Sudbury area; and, b) a 35 km (north-south) by 15 km (east-west) region in the Batchawana Mountain and Montreal River areas of the District of Algoma. Detailed maps showing the locations of the lakes sampled in these areas have been published by Fortescue and Stahl (1987a, 1987b). Throughout this report these study regions are referred to as the Sudbury (shown as a cluster of sample points north of Lake Wanapitei in Figure 2.2) and Algoma study areas (shown as a cluster of sample points north of Sault Ste. Marie in Figure 2.2), respectively.

Water samples from 290 lake sites (i.e. some of the larger lakes were sampled more than once at different locations) were collected: 151 from the Algoma study area; 139 from Sudbury. Access to the lakes was achieved by helicopter as many of the lakes that were sampled are simply too small to accommodate a fixed-wing aircraft.

The water samples were collected in the field in sample-rinsed four-litre "rad jugs", as water column composites of the top 5 metres of water for lakes of sufficient depth, and as surface grab samples (at 0.5 metres below the surface) in shallow lakes. Visual water colour observations, Secchi disc transparency and bottom depth measurements were also made at this time.

Temporary field labs were employed to separate each water sample as follows: 1000 ml polyethylene container for trace metals - HNO_3 preserved; three 500 ml polystyrene containers for pH, nutrients, suspended solids, and major ion analyses; and a 1 oz glass vial for DOC determination. In addition, for measurements of chlorophyll concentrations, a portion of the water sample (up to 1000 ml) was passed through a 1.2 micron filter with the aid of a vacuum pump.

The sample separates were analysed in either the Thunder Bay (for all but the chlorophyll and DOC

measurements) or the Toronto Ministry of the Environment laboratories using the procedures outlined in M.O.E (1981). The determinations that were undertaken were: total chlorophyll *a*, corrected chlorophyll *a*, chlorophyll *b*, dissolved organic carbon, pH, TFE alkalinity (at pH 4.5 and 3.8), TIP alkalinity, conductivity, total Kjeldahl nitrogen (TKN), total phosphorus, suspended solids, sulphate, chloride, calcium, magnesium, sodium, potassium, copper, nickel, zinc, aluminum, manganese, and iron.

Of the 290 lakes sampled, only 134 were included in the remote sensing portion of the study. Unfortunately, the remaining lakes were obscured by cloud cover in the Landsat imagery acquired for the project.

2.3 Satellite Imagery

Matching the three water chemistry data sets with appropriate remote sensing data proved somewhat difficult. Ideal, cloud-free images coinciding precisely with field sampling dates were extremely rare. During the August 1986 field season, the Landsat 5 satellite flew over the sites while we were in the field. An excellent Landsat Thematic Mapper image was acquired for the Algoma study area but a significant section of the TM image of the Sudbury study area was cloud or haze covered. And during the period of this project, no cloud-free image for the Timmins area was available. Even so, the majority of the images that were available were: acquired in July or August in the year that the lakes were sampled in the field; or, acquired in July or August usually one year before or one year after the lakes were sampled in the field. The one major exception to this was the image used for the Parry Sound to Killarney area which was acquired by the Landsat satellite in May, as no July or August cloud-free image could be obtained.

The Landsat 5 scenes that were employed in this project are listed below (Table 2.1). That table identifies the scenes by World Reference System (WRS) path-row designation as well as the official scene identification number. The scenes have been ordered in the list by path-row which

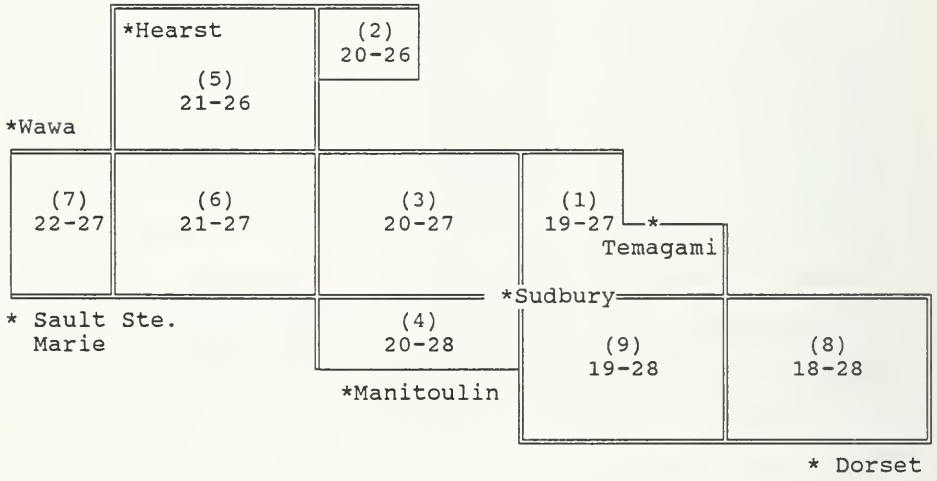
translates to an ordering of from north to south and then from east to west (see also Figure 2.3). The heading "Scene Number" in Table 2.1 is used throughout this report. It is a simpler designation for the Landsat scenes than either path-row or scene identification number, and it indicates the order in which the scenes were processed for this study.

The Canada Centre for Remote Sensing makes available either full Landsat scenes or quadrants. In order to obtain cloud-free imagery for the majority of the study area it was necessary to combine full and quadrant images to obtain the coverage that is shown in Figure 2.3. For Landsat 5, image sidelap increases from 7.3% at the equator to 45% at 50° N latitude (C.C.R.S. 1991). It was possible, therefore, to "fill in" some cloud covered portions of an image using data from an adjacent track. A combination of 23 full and quadrant images were processed to provide Landsat TM coverage of the 28 quadrants depicted in Figure 2.3.

Table 2.1 Listing of the Landsat 5 Thematic Mapper scenes employed.

Scene Number	WRS Path-Row	Image Date	Scene I.D. Number
8	18-28	21-7-86	50872-152533
1	19-27	13-8-86	50895-153030
		31-7-87	51247-153429
9	19-28	25-5-86	50815-153334
2	20-26	17-8-85	50534-154406
3	20-27	1-8-85	50518-154445
4	20-28	1-8-85	50518-154503
5	21-26	7-7-85	50493-155044
6	21-27	7-7-85	50493-155101
		26-7-86	50877-154331
7	22-27	18-8-86	50900-154851

Figure 2.3 Schematic map for the locations of the Landsat TM scenes. Borders of full scenes are shown by ═══ while quadrant borders are shown by ——. Path-row designations are provided for the scenes as well as the study scene numbers (in brackets). Asterisks are used to give a rough indication of a number of cities and towns in the study area. Note that Dorset is just outside the boundaries of Scene 8 (18-28).



The temporal analysis of spectral characteristics of Bowland Lake (see Figure 2.2 for location) was undertaken using eight Landsat images (7 dates). Table 2.2 lists the combination of Landsat MSS and TM images that were employed.

Table 2.2 Landsat scenes available for temporal analyses of Bowland Lake.

Scanner	Date	Satellite Source
MSS	13-7-73	Landsat 1
MSS	8-8-75	Landsat 1
MSS	3-7-80	Landsat 2
MSS	20-7-82	Landsat 3
TM	20-6-84	Landsat 5
TM	22-5-85	Landsat 5
TM	13-8-86	Landsat 5
MSS	13-8-86	Landsat 5

2.4 Data Analyses

> "Solar radiation is of fundamental importance to the entire dynamics of freshwater ecosystems. Almost all energy that drives and controls the metabolism of lakes is derived directly from the solar energy utilized in photosynthesis..... In addition to these direct effects, the absorption of solar energy and its dissipation as heat have profound effects on the thermal structure, water mass stratification, and circulation patterns of lakes..... Therefore, the optical properties of lakes and reservoirs are important regulatory parameters in the physiology and behaviour of aquatic organisms."

These statements from Wetzel (1975, p. 42) are indicative of some of the significant relationships between solar radiation and the dynamics of water bodies. In turn, it is recognized that optical and thermal properties are altered as a result of biotic and abiotic activities within those aquatic ecosystems. Thus, the measurement of optical features of a water body using remote sensing instruments may provide direct or indirect information that can be used to describe those same biotic and abiotic activities.

Radiative transfer theory and the characterization of the optical properties of natural waters provides the physical basis for the remote sensing of water bodies. With respect to the latter, those properties which depend on the impinging radiance of the moment are referred to as **apparent** optical properties; while **inherent** optical properties are those that are intrinsic to the water medium itself and are

not affected by the prevailing distribution of radiance (Kirk 1984). However, apparent properties are largely determined by inherent properties as well, making it theoretically possible to estimate one set from the other.

Unfortunately, the emphasis at this time must be on the phrase "theoretically possible", as radiative transfer is still considered an "**approximate**" (Morel and Prieur 1977) theory even by its advocates. The difficulties that exist in applying the theory are seen in the literature of the past ten years where authors have proposed and then had to extensively refine various aspects of the model (Morel and Prieur 1977; Smith and Baker 1978a, 1978b; Atlas and Bannister 1980; Smith and Baker 1981; Prieur and Sathyendranath 1981; Baker and Smith 1982; Kirk 1984; Kishino et al. 1984; Schanz 1985; Weidemann and Bannister 1986; and others). One of the most telling statements from this group of authors is as follows: for absorption measurements, "there is less discrepancy among the later data, although the agreement is not as good as the published accuracies would suggest. As a consequence, there is still uncertainty in the choice of the most reliable data set." (Smith and Baker 1981, p. 177). Despite the difficulties that do exist, great strides have been made in recent years in applying the concepts of radiative transfer theory (witness, for example, the work done at the Canada Centre

for Inland Waters: Bukata et al. 1981a, 1981b, 1981c; Jerome et al. 1983; Bukata et al. 1985; Jerome et al. 1989).

Nevertheless, remote sensing of water quality is firmly based on the general principles of radiative transfer theory. In the absence of direct measurements of the inherent and most apparent optical properties of water, use is made of an apparent property known as the **reflectance function** - the ratio of upwelling to downwelling vector irradiances. The reflectance ratio is dependent on absorption and back-scattering coefficients (inherent optical properties) which are in turn dependent on the water's content of dissolved and particulate matter (Morel and Prieur 1977; Smith and Baker 1978a; Carder and Steward 1985; and Carder et al. 1986).

The reflectance function is wavelength dependent, with the greatest discrimination occurring in the visible portion of the spectrum, particularly in the blue, green, and blue-green wavelengths. Advantage can be taken of these relationships by remote scanners by "focusing" in on the most relevant wavebands. The objective then is to derive associations between reflectance measurements at various wavelengths acquired from a remote scanner and those water parameters of interest (see, for example: Brooks 1975; Fisher et al. 1979; Scarpace et al. 1979; Lillesand et al.

1983; Verdin, 1985).

There is really no significant difference between the "radiative transfer" and "reflectance function" approaches to water quality monitoring using remotely sensed data. But there seems to be a dichotomy with respect to the strategies of the researchers involved: the former considered "modellers"; the latter considered "empiricists". The dichotomy is probably more apparent than real, but it is true that the former types of applications are dependent on highly sophisticated instrumentation of the optical properties of the target water bodies. As the necessary instrumentation is not always readily available, there are far more "empirical" reports in the literature. Modelling approaches to water quality monitoring is barely dealt with in one of the most recent reviews of the role of remote sensing for surface water assessments (Hockey et al. 1990).

This report fits in with the "empirical" approaches. At the outset of the project in 1986 a "modelling" component had been planned. That component, to be completed by another researcher through a project not funded through the R.A.C. Programme of M.O.E., did not come to fruition.

To deal with the large volumes of imagery data on a small computer (using either a 286 or 386 IBM-compatible),

all of the Landsat scenes were sampled or decimated at a ratio of 1:2, i.e. datasets created using every other scan line and pixel. This was done at the loss of some very small lakes but could not have been avoided with the time and facilities at hand. With the EASI/PACE software of PCI Inc. (PCI 1989), a computer procedure was written to remove terrestrial pixels, outline water bodies with a polygon border, and then compute and record the mean digital numbers for each of the seven TM channels for each lake that was large enough to discriminate.

Multivariate statistical procedures were then employed to derive associations between lake water chemistry parameters and the Landsat reflectance data. Multiple regression, principal components, numerical taxonomic, and multivariate discriminant techniques (Mather 1976; SPSS 1986) were used. Where appropriate, various numeric data transformations, TM band ratios, and stepwise statistical procedures were adopted.

Throughout this project the most successful associations that have been derived have been associated with the following parameters: dissolved organic carbon concentrations, colour, and transparency as measured by Secchi disc depth. This is shown in the following sections where: in Section 3, many lake parameters are employed in an

exploratory way (allowing for a description of the lakes themselves); and then in Section 4, there is a focus on dissolved organic carbon, with related colour and transparency characteristics.

Some of the statistical techniques that have been outlined above were also used in the analysis of temporal reflectance patterns of Bowland Lake. In that portion of the study, however, no image decimation occurred - i.e. no sampling of pixels was undertaken.

3. Exploratory Relationships

3.1 Introduction

The objective of this section of the report is to provide an overall description of the lake parameters that have been compiled for this study. This is accomplished primarily through tabulations of the results of both univariate and multivariate statistical analyses. Inter-relationships are established amongst lake parameters as well as groups of lakes; and associations between Landsat reflectance data and lake parameters/groups are described.

3.2 Descriptive Characteristics

Even though there was at least some water quality data available for each of the 776 lakes in the study area, it is very clear from Table 3.1 that all parameters for all of those lakes were not. However by inspecting the minimum, maximum, and mean values of the lake characteristics presented (Table 3.1) as well as frequency distributions (not shown), it is apparent that these lakes are comparable to the sets of lakes that have been recently described by Neary et al. (1990). As such, they can be considered as reasonably representative of the lakes of the area.

Table 3.1 Descriptive characteristics of lake parameters derived from all lake survey datasets. (n=) indicates the number of lakes used to derive the univariate, descriptive statistics.

Lake Characteristic	(n=)	Minimum	Maximum	Mean
Observed DOC ($mg.L^{-1}$)	(230)	.1	23.5	3.4
Chlorophyll *a* ($\mu g.L^{-1}$)	(121)	.1	4.4	1.4
Secchi depth (m)	(430)	.5	22.0	5.2
Apparent colour (hz)	(264)	-1.8	130.5	16.5
True colour (hz)	(30)	10.0	74.5	39.5
pH	(521)	4.12	8.20	6.34
TIP alkalinity ($mg.L^{-1}$)	(519)	-4.43	180.30	7.55
Conductivity ($\mu mhos.Cm^{-1}$)	(561)	12	419	51
TKN ($\mu g.L^{-1}$)	(325)	40	680	212
NH3 ($\mu g.L^{-1}$)	(230)	0	150	28
NO2 ($\mu g.L^{-1}$)	(230)	1	94	2
NO3 ($\mu g.L^{-1}$)	(230)	5	265	49
Total P ($\mu g.L^{-1}$)	(325)	1	30	6
Ca ($mg.L^{-1}$)	(398)	.72	51.40	4.13
Mg ($mg.L^{-1}$)	(397)	.21	9.26	1.07
Na ($mg.L^{-1}$)	(347)	.25	34.80	1.23
K ($mg.L^{-1}$)	(348)	.1	1.7	.4
SO4 ($mg.L^{-1}$)	(397)	1.24	44.03	9.39
SiO3 ($mg.L^{-1}$)	(230)	.03	2.53	1.00
Cl ($mg.L^{-1}$)	(325)	.01	42.60	1.29
Al ($\mu g.L^{-1}$)	(382)	4	1300	93
Mn ($\mu g.L^{-1}$)	(372)	1	420	44
Fe ($\mu g.L^{-1}$)	(331)	5	1275	74
Zn ($\mu g.L^{-1}$)	(325)	1	110	7
Cu ($\mu g.L^{-1}$)	(325)	1	400	4
Ni ($\mu g.L^{-1}$)	(325)	1	770	14
Pb ($\mu g.L^{-1}$)	(230)	3	22	3
Organic anions ($\mu eq.L^{-1}$)	(398)	.00	241.07	28.87
Calculated DOC ($mg.L^{-1}$)	(398)	.1	23.5	4.0
Trophic status index	(430)	15.41	70.00	38.22

The lakes range in size from just under 2 to just over 85000 hectares, with an average of 863 ha. In terms of mean depth, the equivalent statistics are 0.5, 39.7, and 7.9 m,

respectively. The nutrient and general trophic features, buffering, and trace metal characteristics are very similar in range to those of northeastern Ontario that have been described elsewhere (Pitblado et al. 1980; Keller and Pitblado 1984; Neary et al. 1990).

If remote sensing is to become a tool in lake water quality monitoring, it might be argued that it should do so with minimal amounts of field or "calibration" data. Even so, for this project, there was some concern that the number of lakes with DOC measurements was too low (230). In an effort to increase this number, the Neary et al. (1990) equations relating DOC with apparent or true colour were employed. Thus, the term "Calculated DOC" in Table 3.1 includes: 230 lakes with observed DOC **plus** 168 lakes where DOC is predicted. This combined observed/predicted variable is carried through many of the tables contained in this report but it has not been used very extensively. As Neary et al. (1990) stated, for low colour-low conductivity lakes the equations overestimate DOC.

Another calculated parameter listed in Table 3.1 is that of organic anions (A^-). These are estimated from DOC

and pH using the Lazerte and Dillon (1984) modifications of Oliver's procedure (Oliver et al. 1983):

$$A^- = (K*C_t)/(K+H^+)$$

where $H^+ = 10^{-pH}$

$K = 10^{-pK}$

$pK = 0.96 + 0.90*pH - 0.039*pH^2$

$C_t = 10.9*DOC - 13.7$

Obviously this calculated parameter will provide an overestimate for organic anions for those lakes where DOC has been overestimated using the equations of Neary et al. (1990). Both of the calculated parameters have been maintained in the report for descriptive purposes.

A series of multiple regression analyses were undertaken using lake characteristics as dependent variables and Landsat TM channel data as the predictor variables. This was done in an exploratory manner using all of the parameters listed in Table 3.1, both as given and as transformed to $\log_{10}$ (hydrogen ion concentration for pH).

The resulting multiple correlation coefficients are listed below (Table 3.2). Included are the statistically significant ($P < 0.05$) coefficients greater than 0.30 found for the entire dataset or subdivided by Landsat study scene

Table 3.2 Multiple correlation coefficients for selected lake characteristics using Landsat data as the independent variables. (Blanks have been left where coefficients were not computed; a dash (-) indicates that lakes data were insufficient for computations; all of the coefficients included in the table are statistically significant, $P < 0.05$).

Lake Parameters	All	Landsat Scene Number 1	2	3	4	5	6	7	8	9
Observed DOC ($mg.L^{-1}$)	.70									
Log_{10} DOC	.85	.90	-	.87	.99	-	.93	.85	.72	.54
Calculated DOC ($mg.L^{-1}$)	.54									
Log_{10} Cal. DOC	.74	.92	-	.94	.84	.77	-	.67	.36	.62
Chlorophyll *a* ($\mu g.L^{-1}$)	.66									
Log_{10} Chlorophyll *a*	.82	.72	-	-	-	-	-	.39	-	-
Secchi depth (m)	.70	.84	-	.99	.77	-	.76	.44	.51	.61
Log_{10} Secchi depth	.57									
Apparent colour (hz)	.48									
Log_{10} Apparent colour	.57	.52	-	.99	.47	.82	-	-	.59	.72
TKN ($\mu g.L^{-1}$)	.62									
Log_{10} TKN	.74	.90	-	.92	.80	-	.76	.56	.59	.72
Al ($\mu g.L^{-1}$)	.49	.85	-	.98	.97	.89	.99	.74	-	.27
Log_{10} Al	.39									
Mn ($\mu g.L^{-1}$)	.59	.89	-	-	.90	-	.82	.74	-	.31
Log_{10} Mn	.48									
Organic anions ($\mu eq.L^{-1}$)	.56									
Log_{10} Organic anions	.62	.89	-	.94	.52	.78	-	.66	.38	.68
Trophic status index	.57	.82	-	.99	.78	.98	.82	.45	.39	.63

(see Figure 2.3). As expected, the lake characteristics which remain from this screening process are those which are most optically sensitive or are highly correlated with such parameters. And as expected from previous work (Marshall and Tanis 1989; Pitblado 1984, 1986, 1987a, 1987b, 1991; Pitblado and Dempsey 1989; Pitblado et al. 1987, 1990), DOC relationships are the most consistent. The latter are the focus of Section 4 of this report.

3.3 Principal Components Analysis

To more fully describe the characteristics of the study lakes and the inter-relationships amongst some of the available lake parameters, a principal components analysis (PCA) was undertaken. Given the paucity of lakes with measured parameters, this analysis was limited to those (n=230) having variables which would provide information about the general trophic characteristics of the lakes as well as levels of acidity.

The selected variables loaded (Table 3.3) on three principal components that were judged to be statistically significant (having an eigenvalue ≥ 1.0 and contributing five percent or more to the variance). Together, these three components account for 83% of the variation in the lakes.

As with similar analyses in the past (Pitblado et al. 1980; Keller and Pitblado 1984), the most important component (accounting for 45% of the variance) which distinguishes the differences amongst lakes is nutrient or trophic status (Component I). Six lake characteristics recorded high (absolute value ≥ 0.70) loadings on this component. Five of the loadings were positive (total Kjeldahl nitrogen, apparent colour, trophic status index,

organic anions, total phosphorus) while Secchi depth, as expected, is negatively correlated.

The ionic strength of the surface waters of northeastern Ontario is also very significant (29% of the variance accounted for) with high, positive loadings of conductivity, sulphate, magnesium and calcium (Component II). Slightly less important but still very significant (9%

Table 3.3 Varimax rotated factor matrix of selected lake water parameters (loadings with an absolute value of 0.30 or less are not included).

	Principal Component		
Lake Characteristics	I	II	III
TKN ($\mu g.L^{-1}$)	.9038		
Apparent Colour (hz)	.8906		
Trophic Index	.8777		
Organic Anions ($\mu eq.L^{-1}$)	.8273		
Secchi depth (m)	-.7610		
Total P ($\mu g.L^{-1}$)	.7523		
Conductivity ($\mu mhos.Cm^{-1}$)		.9455	
SO4 ($mg.L^{-1}$)	-.3540	.8737	
Mg ($mg.L^{-1}$)		.8099	.5055
Ca ($mg.L^{-1}$)		.7336	.6222
pH			.9099
TIP Alkalinity ($mg.L^{-1}$)		.3453	.8533
Eigenvalue	5.415	3.518	1.027
% of Variance	45.1	29.3	8.6
Cum. % Variance	45.1	74.4	83.0

of the variation explained) is the acidic status (Component

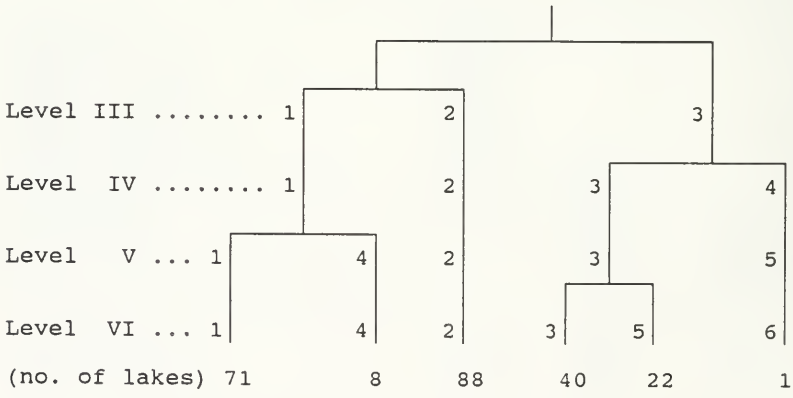
III) of the lakes, with pH and alkalinity as the major contributors to the component and calcium and magnesium appearing as minor loadings.

Although the selection of variables has in many ways "pre-determined" the outcome of the PCA, the analysis clearly highlights the linking of lake parameters with respect to trophic and acidity components. It will now allow us to group lakes based on these components to explore the possibility of deriving such groups using Landsat data.

3.4 Lake Groupings (Numerical Taxonomy)

Factor scores were computed for each of the 230 lakes for the three principal components briefly described above. Those scores were then used to classify the lakes based on squared Euclidean distance as the measure of taxonomic dissimilarity and using Ward's Error as the hierarchical classification algorithm (Mather 1976; SPSS 1986). A greatly simplified dendrogram has been provided (Figure 3.1) to show the nature of the resulting hierarchical classification.

Figure 3.1 Dendrogram showing the general structure of the lake groupings based on factor scores derived from an analysis of three principal components.



The dendrogram has been "sliced" horizontally at four levels, labelled from VI to III. Level VI, for illustrative purposes, indicates that 6 lake groupings or clusters have been identified; Level V - 5 lake groupings; and so on. At each level, the constituent groups have been labelled with a number (as supplied by the SPSS routines) that will allow one to match the dendrogram groupings with the information that is provided in subsequent tables in this section of the report. At the base of the dendrogram, the number of lakes that were placed in each of the Level VI groups has been provided.

A series of multivariate discriminant analyses were undertaken. These were "paired" in the sense that the objectives were to determine the classification accuracies based on these lake groupings when: a) lake parameters were used as the discriminating variables; and, b) Landsat reflectance characteristics were used as the discriminating variables. This was done, in order, from the Level VI to Level III lake groupings. The discriminant classification results for levels VI through IV are briefly outlined below, followed by a fuller description of the Level III groups.

Tables 3.4a and 3.4b tabulate the results of the Level VI discriminant analyses based on lake water parameters and Landsat reflectance data, respectively. The frequency of lakes that are correctly classified will appear in the top left to bottom right diagonal of this and subsequent classification tables. For Level VI (i.e. 6 lake groupings), 91.7% of the lakes are correctly classified when using lake parameters. The proportion of correctly classified lakes plunges to 53.5% when the predictor variables are Landsat reflectance channels. (In each of the Level VI to IV lake groupings it will be noted that there is a lake group with only one lake as a member. Removal of that single-lake group does not alter the proportions of correctly classified lakes).

For Levels V and IV lake groupings, the proportion of correctly classified lakes decreases slightly when the discrimination is based on lake field or chemical characteristics: 89.1% for Level V (Table 3.5a); and, 89.6% for Level IV (Table 3.6a). However, the classification accuracy increases when the analysis is based on Landsat reflectance parameters: 59.1% for Level V (Table 3.5b); and, 69.6% for Level IV (Table 3.6b). As one moves from Level V to Level IV, there is a relatively small shift in the numbers of lakes in each group (i.e. only 8 lakes from Level V added to 71 lakes to form group 1 at Level IV). This

shift results in a combination of lakes which are more uniform (within-group) with respect to lake parameters and more discriminatory (between-group) with repect to reflectance characteristics.

Table 3.4a Discriminant classification results based on selected lake chemistry variables for the Level VI lake groups (see Figure 3.1).

Observed Group	(n)	Predicted Group 1	2	3	4	5	6
Group 1	71	61	7	3	0	0	0
		85.9%	9.9%	4.2%	0.0%	0.0%	0.0%
Group 2	88	2	86	0	0	0	0
		2.3%	97.7%	0.0%	0.0%	0.0%	0.0%
Group 3	40	1	2	37	0	0	0
		2.5%	5.0%	92.5%	0.0%	0.0%	0.0%
Group 4	8	0	0	0	8	0	0
		0.0%	0.0%	0.0%	100.0%	0.0%	0.0%
Group 5	22	0	2	2	0	18	0
		0.0%	9.1%	9.1%	0.0%	81.8%	0.0%
Group 6	1	0	0	0	0	0	1
		0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

Table 3.4b Discriminant classification results based on Landsat reflectance data for the Level VI lake groups (see Figure 3.1).

Observed Group	(n)	Predicted Group 1	2	3	4	5	6
Group 1	71	32	5	10	17	7	0
		45.1%	7.0%	14.1%	23.9%	9.9%	0.0%
Group 2	88	10	51	16	3	8	0
		11.4%	58.0%	18.2%	3.4%	9.1%	0.0%
Group 3	40	7	5	20	5	3	0
		17.5%	12.5%	50.0%	12.5%	7.5%	0.0%
Group 4	8	2	0	0	5	1	0
		25.0%	0.0%	0.0%	62.5%	12.5%	0.0%
Group 5	22	2	3	1	2	14	0
		9.1%	13.6%	4.5%	9.1%	63.6%	0.0%
Group 6	1	0	0	0	0	0	1
		0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

Table 3.5a Discriminant classification results based on selected lake chemistry variables for the Level V lake groups (see Figure 3.1).

Observed Group	(n)	Predicted Group 1	2	3	4	5
Group 1	71	62	7	2	0	0
		87.3%	9.9%	2.8%	0.0%	0.0%
Group 2	88	4	84	0	0	0
		4.5%	95.5%	0.0%	0.0%	0.0%
Group 3	62	4	8	50	0	0
		6.5%	12.9%	80.6%	0.0%	0.0%
Group 4	8	0	0	0	8	0
		0.0%	0.0%	0.0%	100.0%	0.0%
Group 5	1	0	0	0	0	1
		0.0%	0.0%	0.0%	0.0%	100.0%

Table 3.5b Discriminant classification results based on Landsat reflectance data for the Level V lake groups (see Figure 3.1).

Observed Group	(n)	Predicted Group 1	2	3	4	5
Group 1	71	27	6	13	25	0
		38.0%	8.5%	18.3%	35.2%	0.0%
Group 2	88	10	65	10	3	0
		11.4%	73.9%	11.4%	3.4%	0.0%
Group 3	62	11	10	36	5	0
		17.7%	16.1%	58.1%	8.1%	0.0%
Group 4	8	1	0	0	7	0
		12.5%	0.0%	0.0%	87.5%	0.0%
Group 5	1	0	0	0	0	1
		0.0%	0.0%	0.0%	0.0%	100.0%

Table 3.6a Discriminant classification results based on selected lake chemistry variables for the Level IV lake groups (see Figure 3.1).

Observed Group	(n)	Predicted Group 1	2	3	4
Group 1	79	69	8	2	0
		87.3%	10.1%	2.5%	0.0%
Group 2	88	5	83	0	0
		5.7%	94.3%	0.0%	0.0%
Group 3	62	1	8	53	0
		1.6%	12.9%	85.5%	0.0%
Group 4	1	0	0	0	1
		0.0%	0.0%	0.0%	100.0%

Table 3.6b Discriminant classification results based on Landsat reflectance data for the Level IV lake groups (see Figure 3.1).

Observed Group	(n)	Predicted Group 1	2	3	4
Group 1	79	58	6	15	0
		73.4%	7.6%	19.0%	0.0%
Group 2	88	14	64	10	0
		15.9%	72.7%	11.4%	0.0%
Group 3	62	15	10	37	0
		24.2%	16.1%	59.7%	0.0%
Group 4	1	0	0	0	1
		0.0%	0.0%	0.0%	100.0%

Average lake water characteristics for the Level III (i.e. 3 groups, Figure 3.1) lake groups are listed in Table 3.7. For comparison purposes, the mean and modal values for those variables given by Neary et al. (1990) are also provided. The heading "PCA" in Table 3.7 identifies the principal component on which the lake characteristics loaded most highly (see Table 3.3).

The principal component which explained the greatest proportion (45.1%) of the variance within this sample of lakes relates to trophic or nutrient characteristics. This is readily apparent when the first six lake characteristics in Table 3.7 are examined. Group 3 lakes are "average", Group 1 are "above average", and Group 2 are "below average" in terms of nutrient status. And there is a very significant trend towards lower colour and higher transparency as the nutrient characteristics decrease.

The low colour/high transparency lakes (Group 2) are the most acidic and have the lowest mean values for conductivity, magnesium, calcium, and alkalinity. This group of lakes is characterized by only "average" sulphate concentrations even though there are a good number of lakes in this dataset that would have been influenced by the

Table 3.7 Means of lake water characteristics for each of the Level III lake groups. These averages are derived from 230 lakes in Northeastern Ontario. For comparison, values for the mean and modal range from the much larger (n) provincial scene (Neary et al. 1990) are also listed; the values are generally rounded off and n.g. represents not given).

PCA	Lake Characteristics (mean/mode/n)	Average for Study Lakes (n=230)	Lake Groups 1	2	3
I	TKN ($\mu g.L^{-1}$)	216	299	141	216
I	Apparent colour (hz) (n.g./10-20/2066)	13.8	28.3	4.3	8.9
I	Trophic status index	36.79	43.11	31.80	35.82
I	Organic Anions ($\mu eq.L^{-1}$) (52/20-40/3340)	22.94	37.21	9.77	23.44
I	Secchi depth (m)	5.7	3.4	7.8	5.7
I	Total P ($\mu g.L^{-1}$)	7	10	4	7
II	Conductivity ($\mu mhos.L^{-1}$) (n.g./20-40/5617)	49	40	37	77
II	SO4 ($mg.L^{-1}$) per (7/5-10/3599)	11.07	8.26	11.08	14.61
II	MG ($mg.L^{-1}$) (0.6/0.6-1.2/3591)	1.14	1.03	0.76	1.81
II	CA ($mg.L^{-1}$) (7.5/2-4/3702)	4.08	3.62	2.84	6.40
III	pH (6.69/6-7/5982)	6.22	6.37	5.55	6.98
III	TIP Alkalinity ($mg.L^{-1}$) (20/0-13/5911)	4.41	4.45	0.33	10.07

sulphur dioxide emissions in the Sudbury area. There may be a bedrock/geomorphological control affecting some of the Group 3 lakes given their higher sulphate concentrations and their relatively high pH, conductivity, magnesium, calcium, and alkalinity.

As with the Level VI to Level IV groupings of lakes above, these three lake groups were assessed using multivariate discriminant analyses. On the basis of the selected lake characteristics, 90.9% classification accuracy was achieved (Table 3.8a). Only a 68.3% classification accuracy could be attained using Landsat reflectance data (Table 3.8b), although that was an increase from the proportions of lakes correctly classified using the larger number of lake groupings of levels VI and V, and down slightly with respect to the Level IV grouping.

Despite the relatively low classification accuracy, these results are very encouraging. On closer inspection of Table 3.8b, it can be seen that the low colour, high transparency, low nutrient lakes of Group 2 are reasonably

Table 3.8a Discriminant classification results based on selected lake chemistry variables for the Level III lake groups (see Figure 3.1).

Observed Group	(n)	Predicted Group 1	2	3
Group 1	79	72	7	0
		91.1%	8.9%	0.0%
Group 2	88	5	83	0
		5.7%	94.3%	0.0%
Group 3	63	1	8	54
		1.6%	12.7%	85.7%

Table 3.8b Discriminant classification results based on Landsat reflectance data for the Level III lake groups (see Figure 3.1).

Observed Group	(n)	Predicted Group 1	2	3
Group 1	79	58	7	14
		73.4%	8.9%	17.7%
Group 2	88	12	62	14
		13.6%	70.5%	15.9%
Group 3	63	16	10	37
		25.4%	15.9%	58.7%

well differentiated from the high colour, low transparency, high nutrient lakes of Groups 1 and 3. It is clear that the Landsat data are inadequate for fully resolving the lake groupings defined by this relatively large number of variables, many of which are not directly tied to the optical characteristics of water. Even so, the relatively high proportion of lakes that were correctly classified indicates that Landsat reflectance data do have promise as a lake water quality monitoring tool.

The next section of the report outlines the superior success of focusing on but one principal water chemistry parameter that is both a significant discriminator of the nutrient and acidic categories of the relevant lakes and a demonstrably critical link between the optical properties of those lakes and the Landsat reflectance information received using the Thematic Mapper sensor.

4. Predictions of Dissolved Organic Carbon Concentrations

4.1 Introduction

The colour of lake waters is the product of incoming solar radiation, selective scattering and absorption of that radiation by the water itself as well as the materials dissolved and suspended in it, and finally reflection. Of significance here are the facts that: a) colour is frequently used as a water quality indicator; and, b) "colour" is measured by remote sensors. With respect to the former in the context of this report: trophic levels or various states of lake eutrophication are keyed to water colour (Hutchinson 1957; Cole 1979; N.A.S. 1969; Likens 1972; Wetzel 1975); and in the study area, clear water may well flag a lake that has been acidified as a result of contamination by atmospheric pollutants (Yan 1983; Dillon et al. 1984).

Water quality - remote sensing models, typified by the work of the National Water Research Institute of the Canada Centre for Inland Waters (see summary by Jerome et al. 1989) and many others, use the following concentrations as indicators of water quality: chlorophyll *a*; suspended sediment; and dissolved organic carbon. In their remote sensing work for Lake Ontario, Bukata et al. (1981b)

developed a duoisoplethic model (defined with chlorophyll a and suspended sediment), fixing DOC at one concentration level because of its small variability within that lake. By contrast in this report, DOC is the focus because of the minimal amounts of suspended sediments (e.g. silica was at or near the detection limit for the majority of the Algoma and Sudbury study lakes and averaged 1.00 $mg.L^{-1}$) and similarly chlorophyll a concentrations were very low, with a mean value of 1.4 $\mu g.L^{-1}$. It is argued here that suspended sediment and chlorophyll a concentrations contribute little to the colour of the lake waters in the study area.

This emphasis on associating DOC and water colour is certainly not unusual. Some authors (e.g. Wetzel 1975) equate lake water colour almost exclusively with dissolved organic carbon concentrations. For Ontario lakes, Neary et al. (1990) have recently provided a series of regression equations (with r^2 values ranging from 0.575 to 0.888, depending on latitude) which relate colour (both apparent and true) with the concentrations of dissolved organic carbon. And finally, in any study of acidic and non-acidic lakes using remotely sensed data these colour-DOC relationships are extremely important. Almer et al. (1974), Yan (1983), Dillon et al. (1984), and Effler et al. (1985) have demonstrated alterations in transparency which accompany lake acidification and neutralization. Increases

in transparency with acidification have been observed in association with a depletion of DOC, perhaps due to coagulation/adsorption by Al and subsequent losses from the water column (Effler et al. 1985).

The marked effect of DOC-colour on the absorption of light has been tabulated by Wetzel (1975, p. 55) and is illustrated here in graphical form (Figure 4.1). The percent absorption of light is shown for different wavelengths for distilled water and for progressively higher coloured (measured using a colour scale in Pt units) lakes in Wisconsin. Based on these observations we should expect higher Landsat DN values in the blue (TM1 0.45-0.52 μm) and green/yellow (TM2 0.52-0.60 μm) channels for the low coloured-low DOC lakes and perhaps low pH lakes.

To examine the associations that have been outlined above, two questions have been posed. Is colour-DOC a useful water quality indicator for the study lakes? What is the resolving power of Landsat TM with respect to the measurement of colour-DOC? The next two sections of this report attempt to answer these questions, first by employing multivariate discriminant analyses of lake water parameters for several DOC and colour groupings, and then using multiple regression analysis to predict DOC concentrations based on Landsat TM reflectance data.

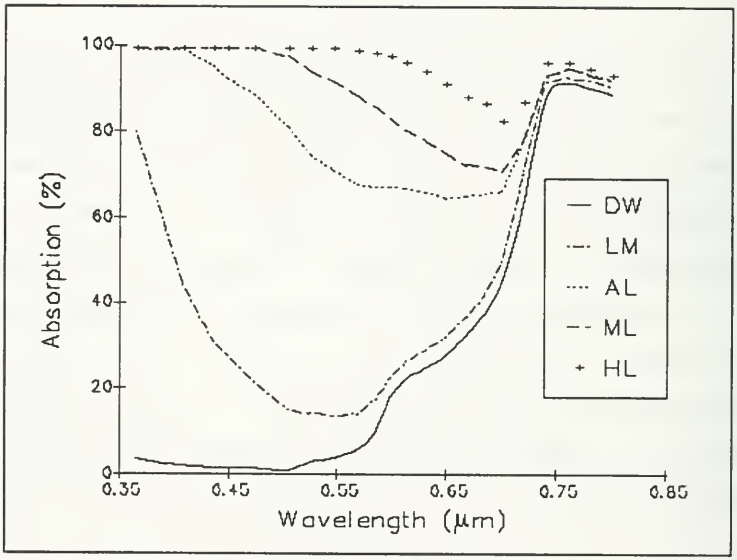


Figure 4.1

Wavelength/absorption relationships (data from Wetzel 1975) for distilled water (DW) and four Wisconsin lakes. The lakes increase in colour (Pt units):

LM - Mendota (6)
AL - Alelaide (28)
ML - Mary (101)
HL - Helmet (264)

4.2 Discriminant Analyses

The 230 study lakes discussed in the previous section of this report (shown on the location map in Figure 2.2) were subdivided into categories limited by their dissolved organic carbon concentrations. Three sets were so employed. In the first, ten category limits were arbitrarily established with 1 $mg.L^{-1}$ intervals (0.0-1.0, 1.1-2.0, etc.). For the remaining two sets, the choice of the category intervals was guided by the frequency distribution of DOC in the 2581 Ontario lakes examined by Neary et al. (1990). In their work they employed a 2 $mg.L^{-1}$ interval which was adopted here for the second set of DOC categories. And finally, the class limits for the third set were chosen as follows: 0.0-2.0, 2.1-6.0, and > 6.0. An inspection of the histogram in Neary et al. (1990, p. 45) shows; a relatively small but distinct class of lakes with DOC concentrations less than 2.0 $mg.L^{-1}$; the modal distributions with concentrations between 2.0 and 6.0 $mg.L^{-1}$; and the remainder greater than 6.0 $mg.L^{-1}$.

For comparison purposes, 118 lakes were selected from the 230 because of the availability of visual water colour observations. These are lakes from the smaller Algoma (n=51) and Sudbury (n=67) surveys that were undertaken in 1986 (see Section 2.2). In those surveys, colour

designations were assigned in the field by one observer (Hubert Stahl, formerly of the Ontario Geological Survey). The designations included ten terms such as blue, bluish green, greenish blue, brown, etc. They were generalized into three categories: blue, green, and brown (Pitblado 1991). The three colour designations used here are preferable to the more accurate but awkward terms 'bluish', 'greenish', and 'brownish'. Note that, for the most part, brown does not refer to "brown water lakes" in the sense of swamps, bogs, or dystrophic lakes (Oliver et al. 1983).

These four sets of lake groupings were then examined to confirm or deny the utility of DOC-colour as water quality indicators and, if confirmed, to determine the nature of the lake characteristics associated with these various groupings. The same lake characteristics that were employed in the principal components analysis (listed in Tables 3.3 and 3.7) were used in a discriminant analysis of each of the four sets of lake groupings. As a reminder, these variables, in the order that they appeared in the PCA, were: total Kjeldahl nitrogen, apparent colour, trophic status index, organic anions, Secchi disc depth, total phosphorus, conductivity, sulphate, magnesium, calcium, pH, and TIP alkalinity.

The discriminant classification results for these four

sets of lake groupings are shown in Tables 4.1 to 4.4. All of the DOC groupings are extremely well classified (> 90%). For the DOC 10-group (Table 4.1), 6-group (Table 4.2) and 3-group (Table 4.3) subdivision of the study lakes, the proportions of lakes correctly classified into these groups are 93.0%, 93.9%, and 90.9%, respectively. And even the loosely defined visual colour grouping of lakes produces a relatively high (83.1%) proportion of correctly classified lakes (Table 4.4). Inspection of these four tables also indicates that where a lake is misclassified it usually is placed by the discriminant analysis procedure in a group or class immediately adjacent to the correct class.

For illustrative and descriptive purposes, tables and bar charts of the mean values of **all** lake variables available (i.e. not just the smaller number of variables selected for the principal components analysis) were prepared. These include: a) for the six-class DOC grouping - bar charts in Appendix A; b) for the three-class DOC grouping - Table 4.5; and, c) for three-class visual water colour grouping - Table 4.6 and bar charts in Appendix B).

Table 4.1 Discriminant classification results based on selected lake water characteristics amongst ten DOC ($mg.L^{-1}$) categories.

Observed Groups	(n)	Predicted Groups 1	2	3	4	5	6	7	8	9	10
Group 1 0.0-1.0	17	13	4	0	0	0	0	0	0	0	0
Group 2 1.1-2.0	22	0	22	0	0	0	0	0	0	0	0
Group 3 2.1-3.0	67	2	1	63	1	0	0	0	0	0	0
Group 4 3.1-4.0	50	0	0	2	47	1	0	0	0	0	0
Group 5 4.1-5.0	31	0	0	0	1	30	0	0	0	0	0
Group 6 5.1-6.0	29	0	0	0	0	0	25	4	0	0	0
Group 7 6.1-7.0	6	0	0	0	0	0	0	6	0	0	0
Group 8 7.1-8.0	3	0	0	0	0	0	0	0	3	0	0
Group 9 8.1-9.0	2	0	0	0	0	0	0	0	0	2	0
Group 10 > 9.0	3	0	0	0	0	0	0	0	0	0	3

Table 4.2 Discriminant classification results based on selected lake water characteristics amongst six DOC ($mg.L^{-1}$) categories.

Observed Group	(n)	Predicted Group 1	2	3	4	5	6
Group 1	39	38	1	0	0	0	0
0.0-2.0		97.4%	2.6%	0.0%	0.0%	0.0%	0.0%
Group 2	117	5	112	0	0	0	0
2.1-4.0		4.3%	95.7%	0.0%	0.0%	0.0%	0.0%
Group 3	60	0	1	52	7	0	0
4.1-6.0		0.0%	1.7%	86.7%	11.7%	0.0%	0.0%
Group 4	9	0	0	0	9	0	0
6.1-8.0		0.0%	0.0%	0.0%	100.0%	0.0%	0.0%
Group 5	2	0	0	0	0	2	0
8.1-10.0		0.0%	0.0%	0.0%	0.0%	100.0%	0.0%
Group 6	3	0	0	0	0	0	3
> 10.0		0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

Table 4.3

Discriminant classification results based on selected lake water characteristics amongst three DOC ($mg.L^{-1}$) categories.

Observed Group	(n)	Predicted Group 1	2	3
Group 1 0.0-2.0	39	38 97.4%	1 2.6%	0 0.0%
Group 2 2.1-6.0	177	13 7.3%	159 89.8%	5 2.9%
Group 3 > 6.0	14	0 0.0%	2 14.3%	12 85.7%

Table 4.4

Discriminant classification results based on selected lake water characteristics amongst three visual water colour categories.

Observed Group	(n)	Predicted Group Blue	Green	Brown
Group 1 Blue	18	18 100.0%	0 0.0%	0 0.0%
Group 2 Green	80	5 6.2%	63 78.8%	12 15.0%
Group 3 Brown	20	0 0.0%	3 15.0%	17 85.0%

Table 4.5 Means of lake water characteristics for each of three DOC categories.

Lake Characteristics	All	DOC Categories ($mg.L^{-1}$) 0.0-2.0	2.1-6.0	> 6.0
Chlorophyll *a* ($\mu g.L^{-1}$)	1.4	0.5	1.9	3.0
Secchi depth (m)	5.6	8.9	5.0	2.9
Apparent colour (hz)	16.5	3.8	13.7	59.8
True colour (hz)	39.5	0.0	12.5	46.2
pH	6.21	5.15	6.37	6.65
TIP alkalinity ($mg.L^{-1}$)	5.71	-0.40	6.07	11.03
Conductivity ($\mu mhos.Cm^{-1}$)	45	36	47	46
TKN ($\mu g.L^{-1}$)	212	108	228	395
NH3 ($\mu g.L^{-1}$)	28	21	30	28
NO2 ($\mu g.L^{-1}$)	2	1	1	15
NO3 ($\mu g.L^{-1}$)	49	57	47	54
Total P ($\mu g.L^{-1}$)	6	3	7	13
Ca ($mg.L^{-1}$)	4.10	2.38	4.25	5.34
Mg ($mg.L^{-1}$)	1.06	0.64	1.10	1.34
Na ($mg.L^{-1}$)	1.22	0.64	1.38	1.18
K ($mg.L^{-1}$)	0.4	0.4	0.4	0.4
SO4 ($mg.L^{-1}$)	9.38	11.16	9.59	6.36
SiO3 ($mg.L^{-1}$)	1.00	0.89	1.02	1.00
Cl ($mg.L^{-1}$)	1.29	0.31	1.57	1.06
Al ($\mu g.L^{-1}$)	93	208	67	83
Mn ($\mu g.L^{-1}$)	44	109	28	38
Fe ($\mu g.L^{-1}$)	74	50	76	153
Zn ($\mu g.L^{-1}$)	7	10	7	6
Cu ($\mu g.L^{-1}$)	4	3	4	3
Ni ($\mu g.L^{-1}$)	14	13	15	2
Pb ($\mu g.L^{-1}$)	3	3	3	3
Organic Anions ($\mu e.q.L^{-1}$)	28.87	2.10	25.00	77.56
Trophic Status Index	36.95	30.17	37.97	45.87

Table 4.6 Means of lake water characteristics for each of three visual water colour categories.

Lake Characteristics	All	Water Colour Categories Blue	Green	Brown
Observed DOC ($mg.L^{-1}$)	2.4	0.3	2.8	4.2
Chlorophyll *a* ($\mu g.L^{-1}$)	1.3	0.2	1.5	2.0
Secchi depth (m)	7.3	12.8	5.7	3.6
Apparent Colour (hz)	2.9	1.9	3.9	0.0
pH	5.47	4.76	5.76	5.89
TIP alkalinity ($mg.L^{-1}$)	1.01	-1.01	1.59	2.54
Conductivity ($\mu mhos.Cm^{-1}$)	31	37	28	28
TKN ($\mu g.L^{-1}$)	175	68	186	272
NH3 ($\mu g.L^{-1}$)	23	28	17	0
NO2 ($\mu g.L^{-1}$)	1	1	1	0
NO3 ($\mu g.L^{-1}$)	65	92	38	0
Total P ($\mu g.L^{-1}$)	4	2	4	6
Ca ($mg.L^{-1}$)	2.31	2.05	2.35	2.54
Mg ($mg.L^{-1}$)	0.57	0.54	0.53	0.64
Na ($mg.L^{-1}$)	0.55	0.55	0.53	0.58
K ($mg.L^{-1}$)	0.3	0.4	0.3	0.2
SO4 ($mg.L^{-1}$)	8.54	11.33	7.48	6.81
SiO3 ($mg.L^{-1}$)	0.89	0.74	1.04	0.00
Cl ($mg.L^{-1}$)	0.19	0.22	0.19	0.17
Al ($\mu g.L^{-1}$)	181	292	129	122
Mn ($\mu g.L^{-1}$)	78	141	51	41
Fe ($\mu g.L^{-1}$)	73	37	53	128
Zn ($\mu g.L^{-1}$)	6	9	5	6
Cu ($\mu g.L^{-1}$)	2	2	1	3
Ni ($\mu g.L^{-1}$)	6	9	4	4
Pb ($\mu g.L^{-1}$)	4	4	4	0
Organic Anions ($\mu e.q.L^{-1}$)	14.86	0.00	15.67	28.92
Trophic Status Index	34.29	24.22	36.04	42.61

The discriminant analyses (Tables 4.1 to 4.4) and descriptive tabulations (Tables 4.5 and 4.6 and Appendices A and B) clearly show that DOC is a significant water quality indicator in terms of both those variables that relate to trophic status and those variables that relate to lake acidity, recognizing that even these two categories are often related to each other. As a summary and acknowledging a degree of variability, the lake water characteristics are grouped below according to their general relationship with increasing or decreasing DOC-colour (for those lake variables where the trends are not clear or are ambiguous, the parameter has not been listed):

Variables which increase with increasing DOC-colour

- chlorophyll *a*; apparent colour; true colour; pH; alkalinity; total Kjeldahl nitrogen; nitrite; total phosphorus; calcium; silica; iron; organic anions; trophic status index

Variables which decrease with increasing DOC-colour

- Secchi disc depth; sulphate; zinc; nickel; lead; aluminum and manganese (which decrease then increase again with increasing DOC-colour)

If DOC can be accepted as a reasonable indicator of water quality, as shown above, then it would be desirable to use remotely sensed data to predict DOC to act as a surrogate measure of the acidity and trophic status of the study lakes.

4.3 Regression Analyses

To determine whether Landsat data could be used to predict the DOC concentrations of the study lakes, a stepwise multiple regression analysis was undertaken using DOC as the dependent variable and the DN values from the TM channels as the independent variables.

The lakes employed for this analysis are the same 230 (less three lakes which appeared to have haze-affected Landsat pixels) that have been the focus above and in Section 3 of this report. This represents slightly less than 0.1% of the lakes in all of Ontario (Cox 1978) but close to 10% of the lakes examined by Neary et al. (1990). Earlier (Section 3), it had been indicated that a visual inspection of the descriptive characteristics for these lakes with the histograms and tables of Neary et al. (1990) showed that these lakes were very similar in their principal features. This point is raised here because half of the study lakes come from the Algoma and Sudbury survey areas and there is one Landsat scene and one quadrant where no DOC values had been obtained. The latter area (study scenes 2 and 5, see Figure 2.3) is located in the northern most portion of the study area in the Hearst-Kapuskasing region. On the other hand, Figure 2.2 and Table 4.7 do indicate that this group of 227 lakes is fairly well distributed

geographically throughout the primary study area of Northeastern Ontario. Later figures will also demonstrate that the frequency distributions of both observed and predicted DOC match the frequency distribution of Neary et al. (1990) very well.

Table 4.7 Crosstabulation showing the frequency distribution (number of study lakes) of **observed** DOC ($mg.L^{-1}$) measurements by Landsat TM scene location (Figure 2.3). The Sudbury survey lakes are located in scene 1 (19-27); the Algoma survey lakes are located in scene 7 (22-27).

Landsat WRS	No.	DOC Categories 0.0-2.0	2.1-6.0	> 6	Row Totals
19-27	1	41	39	1	81 35.7%
20-27	3	11	22	1	34 15.0%
20-28	4	3	6	1	10 4.4%
21-27	6	2	6	1	9 4.0%
22-27	7	3	46	2	51 22.5%
18-28	8	0	8	10	18 7.9%
19-28	9	6	11	7	24 10.6%
Column Totals		66 29.1%	138 60.8%	23 10.1%	227 100.0%

In Section 3 (Table 3.2) of this report, it was indicated that a multiple correlation coefficient of 0.828 ($P < 0.05$) was generated using observed DOC as the dependent variable and Landsat reflectance channels and transforms as the independent variables. The equation from which that coefficient was derived is shown below (Eqn. 1). Because of the distribution of sample lakes between the two predominant sulphur deposition zones (Zone 7 and Zone 4), the Landsat images and the sample lakes were subdivided into two groups and multiple regression analyses applied to each of them separately.

An "East" set of lakes/images was defined which incorporated study scenes 1, 8 and 9; the "West" included the remaining scenes from 2 to 7 (see Figure 2.3). The resulting regression equations are shown as Eqn. 2 and Eqn. 3 for East and West, respectively. The multiple correlation coefficients for these subsets of the study area increased to 0.860 ($P < 0.05$) and 0.869 ($P < 0.05$), again for the East and West subsets, respectively.

[Eqn. 1]

$$DOC_{All} = -56.133783 - 0.002149(TM1^2) - 1.465070(TM1/TM3) - 0.311107(TM7) + 44.171897(Log_{10}\ TM1) - 4.406605(Log_{10}\ TM4) + 0.005861(TM4^2)$$

[Eqn. 2]

$$DOC_{East} = 1.458353 - 1.322580\ (TM1/TM3) - 0.800731(\text{Log}_{10}\ TM7) - 0.016931\ (TM2^2) + 0.624895(TM2)$$

[Eqn. 3]

$$DOC_{West} = -18.931044 - 0.003304(TM1^2) + 15.313563(\text{Log}_{10}\ TM3) - 0.005380(TM4^2) - 0.162534(TM7) - 86.182163(TM2/TM1) + 9.617717(\sqrt{}TM2)$$

In the lakes of the study area (n=227), the observed concentrations of DOC range from 0.1 to 23.5 $mg.L^{-1}$, with a mean of 3.49 $mg.L^{-1}$ and a standard deviation of 2.61 $mg.L^{-1}$. The mean value for calculated DOC (i.e. observed plus estimates from apparent and true colour, n=398) is slightly higher at 4.02 $mg.L^{-1}$, with minimum, maximum and standard deviations almost identical. These average values are less than the mean (6.3 $mg.L^{-1}$) reported by Neary et al. (1990) using 2581 lakes plus 759 lakes for which DOC could have been over-estimated. Converted to common logarithms for comparisons with the Landsat predicted DOC values, the minimum, maximum, mean, and standard deviations for the study lakes are as follows: -1.00, 1.37, 0.41, 0.40 for the observed DOC; and, -1.00, 1.37, 0.50, 0.35 for the calculated DOC.

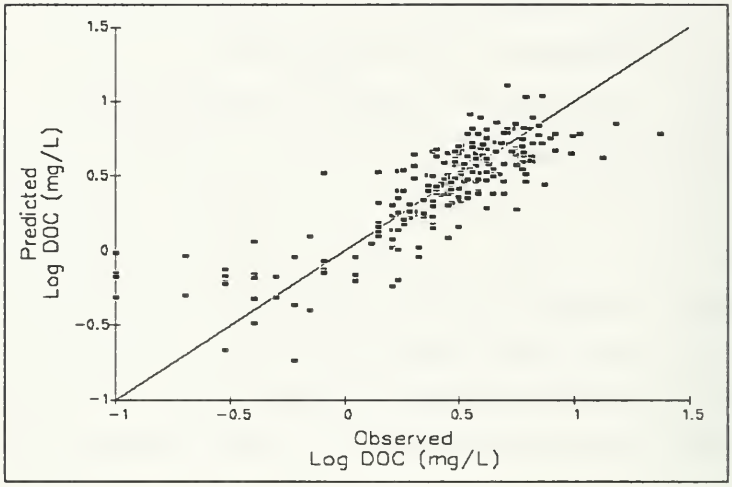


Figure 4.2 Predicted DOC vs Observed DOC based on Landsat TM data for all scenes of the study area.

Observed DOC concentrations have been plotted against Landsat predicted DOC in Figures 4.2 to 4.4. The illustration above (Figure 4.2) was generated by matching the observed DOC for 227 lakes with predicted DOC for those same lakes using Equation 1. As one would expect with a multiple correlation coefficient of 0.828, the lakes cluster along the 1:1 line that has been added to the figure. The predicted DOC tends to be over-estimated for very low observed DOC lakes and under-estimated for relatively high DOC lakes. In comparison with the descriptive information provided above, the predicted DOC values are -0.74, 1.10,

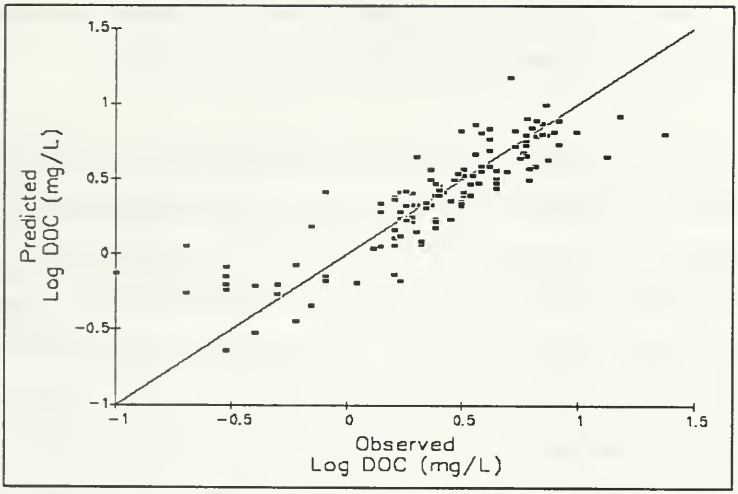
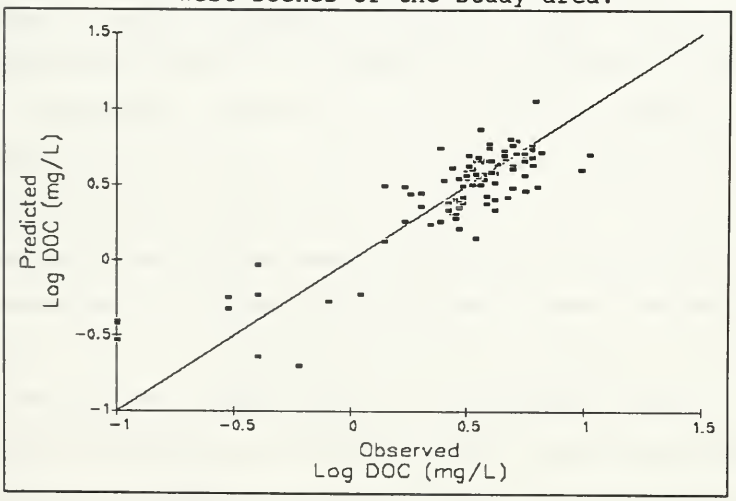


Figure 4.3 Predicted DOC vs Observed DOC based on Landsat TM data for East scenes of the study area.

Figure 4.4 Predicted DOC vs Observed DOC based on Landsat TM data for West scenes of the study area.



0.41, and 0.33 for the minimum, maximum, mean, and standard deviation, respectively.

Similar over- and under-estimations occur when comparing observed and predicted DOC for the eastern images (Figure 4.3, derived using Equation 2) although the differences are not as great. The average value (common logarithms of DOC in $mg.L^{-1}$) for both the observed and predicted DOC for these lakes (n=123) is 0.38. The range of predicted DOC values for these lakes (with statistics for the observed DOC in brackets) was -0.64(-1.00), 1.17(1.37), 0.36(0.42), for the minimum, maximum, and standard deviation, respectively. Even less scatter from the 1:1 line is apparent for the 104 lakes in the western images (Figure 4.4, derived using Equation 3). The comparable statistics, again with the observed DOC values in brackets, were: -0.70(-1.00), 1.05(1.02), 0.45(0.45), 0.33(0.38) for the minimum, maximum, mean, and standard deviation, respectively.

To further compare the observed and predicted DOC, the values were back-transformed into the following categories ($mg.L^{-1}$): Category 1 0.0-2.0; Category 2 2.1-4.0; Category 3 4.1-6.0; Category 4 6.1-8.0; Category 5 8.1-10.0; Category 6 >10.0. Tabulations of the differences (Tables 4.8 to 4.10) were created by subtracting the predicted DOC

Table 4.8 Frequency distribution of differences between observed and predicted DOC categories using Equation 1 for all Landsat scenes in the study area.

Landsat Scene	Difference Categories (Obs - Pred) -3	-2	-1	0	+1	+2	+3
1 (19-27)	1	1	8	60	10	1	
3 (20-27)			5	24	4	1	
4 (20-28)				6	3	1	
6 (21-27)			5	3		1	
7 (22-27)	1	3	19	19	7	2	
8 (18-28)			2	5	6	5	
9 (19-28)		1	1	13	5	2	2
Number	2	5	40	130	35	13	2
%	.9	2.2	17.6	57.3	15.4	5.7	.9

category from the observed DOC category and then crosstabulating the results by Landsat scene. This provides a summary of the differences between observed and predicted DOC as well as an indication of scene-to-scene variability.

When Equation 1 is employed, 57.3% of the lakes (Difference Category 0 in Table 4.8; see also Figure 4.2) fall within the same DOC category. The DOC of almost

Table 4.9 Frequency distribution of differences between observed and predicted DOC categories using Equation 2 for the eastern Landsat scenes.

Landsat Scene	Difference Categories (Obs - Pred) -3	-2	-1	0	+1	+2	+3
1 (19-27)	1	3	10	57	9	1	
8 (18-28)		1	2	9	5	1	
9 (19-28)			3	14	3	3	1
Number	1	4	15	80	17	5	1
%	.8	3.3	12.2	65.0	13.8	4.1	.8

Table 4.10 Frequency distribution of differences between observed and predicted DOC categories using Equation 3 for the western Landsat scenes.

Landsat Scene	Difference Categories (Obs - Pred) -2	-1	0	+1	+2	+3
3 (20-27)		4	24	6		
4 (20-28)			4	5	1	
6 (21-27)		3	5			1
7 (22-27)	2	13	30	5		1
Number	2	20	63	16	1	2
%	1.9	19.2	60.6	15.4	1.0	1.9

eighteen percent of the lakes are over-estimated by one DOC category (the -1 column in Table 4.8), i.e. up to 2 $mg.L^{-1}$; while close to fifteen percent are under-estimated by one DOC category (+1). Only 9.7% of the lakes are over- or under-estimated by more than one DOC category.

Similar tables have been prepared for the application of Equation 2 to the eastern Landsat scenes and Equation 3 to the western Landsat scenes. Ninety-one percent of the lakes in the east and 95.2% of the lakes in the west fall within the same observed/predicted DOC category or within the adjacent category. And as illustrated in Figures 4.5 to 4.7, the frequency distributions of observed and predicted DOC by DOC categories are almost identical when only those lakes with observed DOC are being compared.

Of particular interest are the frequency distributions shown in Figure 4.8 comparing predicted DOC with the frequency distribution of DOC for 2581 Ontario lakes. In the process of gathering Landsat spectral values for lakes with water chemistry characteristics (i.e. 230 with DOC, 776 with at least some water chemistry data), the reflectance values of a large number of lakes with unknown field data were also acquired, for a total of 1082 lakes.

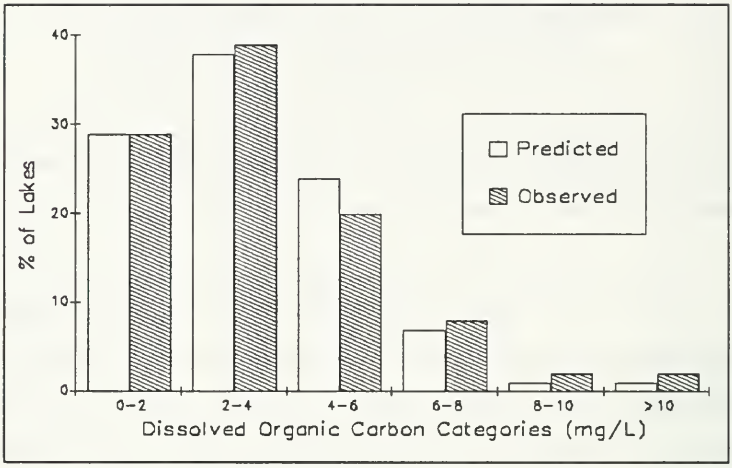
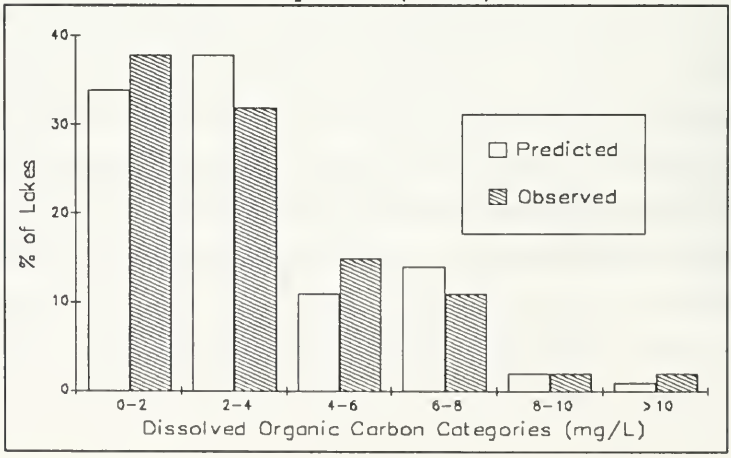


Figure 4.5 Frequency distributions of observed and Landsat predicted DOC by DOC categories for the entire study area (n=227).

Figure 4.6 Frequency distributions of observed and Landsat predicted DOC by DOC categories for the eastern half of the study area (n=123).



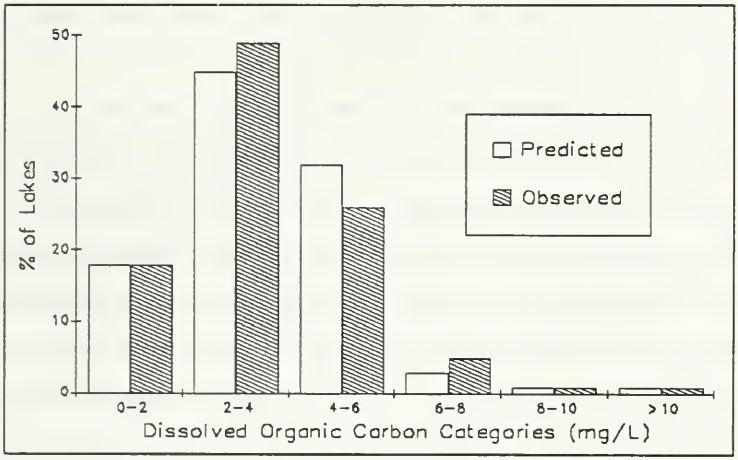


Figure 4.7 Frequency distributions of observed and Landsat predicted DOC by DOC categories for the western half of the study area (n=104).

Figure 4.8 Frequency distributions of Ontario lakes (Neary et al. 1990) by DOC categories compared with Landsat predicted DOC.

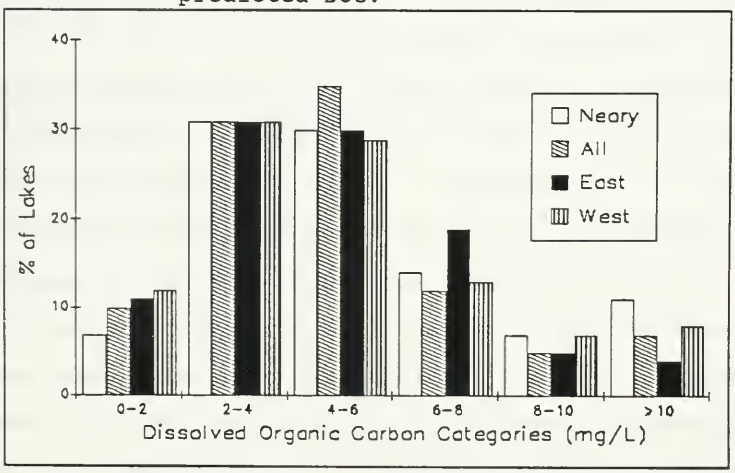


Figure 4.8 shows the results of applying Equations 1 to 3 to the total Landsat reflectance set whether the sampled lake had field observed DOC measurements or not. That is: Equation 1 was used for all 1082 lakes with acquired reflectance data; Equation 2 was used for 608 of the 1082 lakes located within the eastern Landsat images; and Equation 3 used with the remaining 474 lakes located within the area of the western Landsat images. The data for the Ontario lakes, labelled "Neary" to acknowledge the source, are estimates from the figure in Neary et al. (1990, p. 45) showing the distribution of DOC by DOC categories.

With the possible exception of the predictions in the 6-8 $mg.L^{-1}$ category for the east images, the frequency distributions for the Landsat predicted DOC match that of Ontario lakes very well. At the lower end of the scale (0-2 $mg.L^{-1}$), there are a higher number of low DOC lakes than the proportion for Ontario lakes. This probably reflects the significant influence of the high sulphur deposition zone (Zone 7) of the Sudbury. And it would appear as if Northeastern Ontario has a lower proportion of very high DOC (i.e. > 10 $mg.L^{-1}$) lakes. Neary et al. (1990) report DOC values for 6 lakes in the range from 31 to 58 $mg.L^{-1}$, and in their frequency distribution plot provide for DOC categories from 12 to 30 $mg.L^{-1}$. For the lakes available for the analysis in this report, "high" DOC meant lakes in the range

10-12 $mg.L^{-1}$ and one lake with a DOC value of 23.5 $mg.L^{-1}$.

To illustrate the relationships between predicted dissolved organic carbon concentrations and all other lake water parameters, linear correlation coefficients were computed and are reported in Appendix C. That appendix includes the following set of correlation coefficients for the entire study area, and separately for the east and west sets of images:

- correlations of **observed** Log_{10} DOC with the 28 lake parameters listed in Table 3.1 (i.e. **All** lake characteristics available, not just those used in the earlier principal components analysis)

- correlations of **predicted** Log_{10} DOC with all lake characteristics

- correlations of **observed** Log_{10} DOC with all lake characteristics **transformed** to Log_{10} (with pH as hydrogen ion concentration)

- correlations of **predicted** Log_{10} DOC with all lake characteristics **transformed** to Log_{10} (with pH as hydrogen ion concentration)

Given the information on data availability (Table 3.1), the correlations listed above were undertaken with lake numbers ranging from 30 to 521. The objective was to see whether there were any differences in the relationships between predicted DOC vs other water parameters and observed DOC vs other water parameters. As hoped for, the tabula-

tions in Appendix C generally show the same pattern for the respective associations, i.e. the correlations are as good or as poor for predicted DOC as they are for observed DOC.

These correlations of DOC, either predicted or observed, with other water parameters are further discussed in the Section 4.5 of this report. As a summary, however, it can be noted that in their Lakeshore Capacity Study, Dillon et al. (1986) use DOC as one of the bundle of parameters that are useful in defining and predicting the trophic status of lakes. Similarly, throughout this report it has been indicated that in the Sudbury area, at least, there are strong correlations between DOC and pH, DOC and Secchi depth, and between pH and Secchi depth. Therefore, the capability of using satellite data for estimating DOC concentrations of inland lakes will be of great benefit for regional lake surveys in terms of determining DOC itself and for making predictions of those water parameters that can be estimated from DOC.

4.4 Image Processing and Mapping

4.4.1 Introduction

Adhering to the philosophy of "a picture is worth a thousand words", this section of the report provides little discussion but is used to illustrate the applications of the derived DOC prediction equations discussed in Section 4.3. The emphasis here is on the spatial display (mapping) of the resulting Landsat image interpretations. Two approaches have been adopted, both using the mapping capabilities of geographical information systems (G.I.S.). The first considers the study lakes as points in space suitable for **vector** (point) mapping; the second considers water bodies throughout the area as entities with spatial dimensions that can be mapped in a **raster** format directly from the Landsat images. The latter form of mapping is being used to prepare a series of predicted DOC maps for the entire study area.

4.4.2 Vector (Point) Mapping

As described in Section 2.4, the process employed to acquire Landsat reflectance data for the lakes that were used to generate the regression models (Section 4.3) involved the creation of an image analysis **bitmap** or mask for 1082 lakes scattered throughout the study area. All of

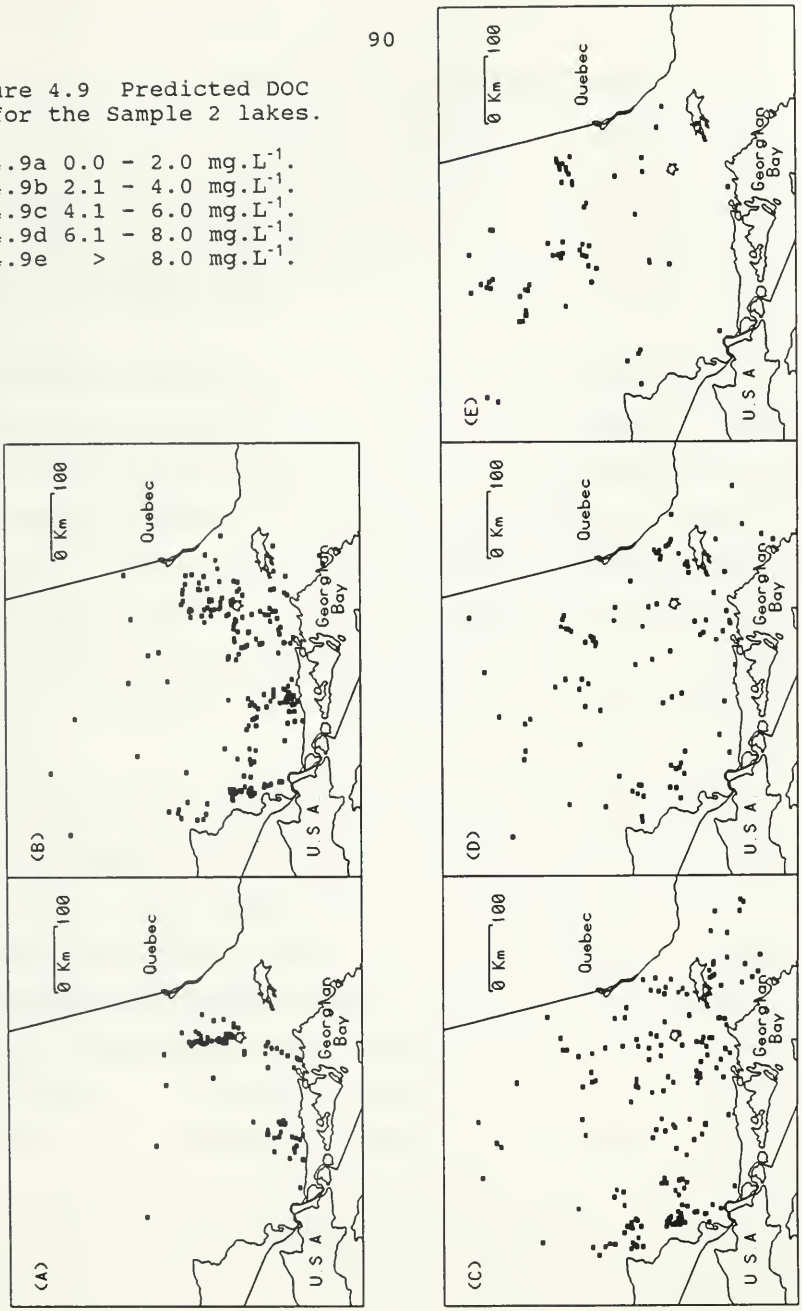
the lake pixels under a bitmap were used to compute the mean value for each Landsat channel for each of the sampled lakes. These data were then employed to create the regression equations that have been discussed earlier.

During this data collection process, the latitude and longitude of those bitmaps that could be matched with the lakes data from the M.O.E. and M.N.R. datasets (Section 2.2) were recorded. Therefore, in the database created for this research project, these lakes (n=775, including the 230 used to generate the DOC regression equations) have to be considered as "points" in geographical space. They can be georeferenced by latitude and longitude but have no other spatial dimensions that are mappable.

For each of these 775 lakes, Landsat-derived DOC predictions were made and then subdivided into the following classes ($mg.L^{-1}$): 0.0 - 2.0; 2.1 - 4.0; 4.1 - 6.0; 6.0 - 8.0; > 8.0. In this section of the report, the 230 lakes used to create the regression equations are referred to as Sample 1 and the 775 lakes are referred to as Sample 2. The series of maps provided as Figures 4.9a to 4.9e shows the distribution of the Sample 2 study lakes in terms of their predicted DOC concentrations. Note again that the DOC concentrations of less than a third of these lakes were known during the course of this research project.

Figure 4.9 Predicted DOC for the Sample 2 lakes.

4.9a 0.0 - 2.0 $mg.L^{-1}$.
4.9b 2.1 - 4.0 $mg.L^{-1}$.
4.9c 4.1 - 6.0 $mg.L^{-1}$.
4.9d 6.1 - 8.0 $mg.L^{-1}$.
4.9e > 8.0 $mg.L^{-1}$.



To prepare these maps the latitude and longitude coordinates were transformed to Lambert conformal coordinates using the pc ARC/INFO GIS system (ESRI 1988). The lake points were then overlayed onto a base map digitized by the National Atlas Information System (Ottawa).

While these maps (Figs. 4.9a to 4.9e) are extremely useful in showing the distribution of lakes with predicted DOC concentrations, it is difficult to examine them further as there is no basis for comparison. Therefore, three additional series of maps have been prepared that should be read together with Figs. 4.9a to 4.9e and the discussion of observed vs predicted DOC concentrations that has been provided in the previous section of this report.

The additional three series of maps employ **only** those lakes of the 775 which had observed DOC measurements (i.e. 230 lakes). Figures 4.10a to 4.10e show the locations of lakes with **observed** DOC concentrations and Figures 4.11a to 4.11e show the locations of lakes with **Landsat-predicted** DOC concentrations. Each of these series of maps employ the 2-$mg.L^{-1}$ DOC categories that have been used for Figures 4.9a to 4.9e as well as in the discussion provided in Section 4.3. The maps in Figures 4.12a to 4.12e locate lakes by differences between observed and predicted DOC categories.

Figure 4.10 Observed DOC for the Sample 1 lakes.

4.10a 0.0 - 2.0 $mg.L^{-1}$.
4.10b 2.1 - 4.0 $mg.L^{-1}$.
4.10c 4.1 - 6.0 $mg.L^{-1}$.
4.10d 6.1 - 8.0 $mg.L^{-1}$.
4.10e > 8.0 $mg.L^{-1}$.

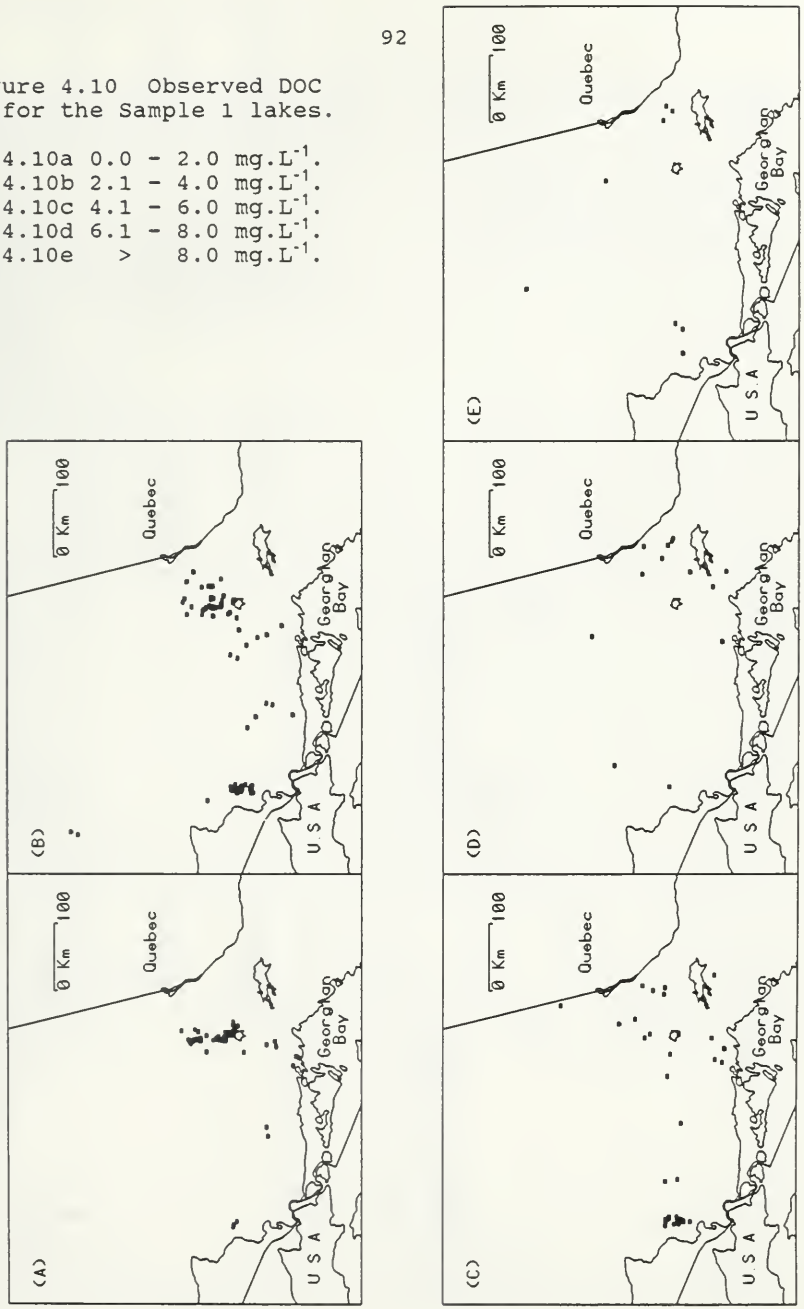


Figure 4.11 Predicted DOC for the Sample 1 lakes.

4.11a 0.0 - 2.0 mg.L^{-1}.
4.11b 2.1 - 4.0 mg.L^{-1}.
4.11c 4.1 - 6.0 mg.L^{-1}.
4.11d 6.1 - 8.0 mg.L^{-1}.
4.11e > 8.0 mg.L^{-1}.

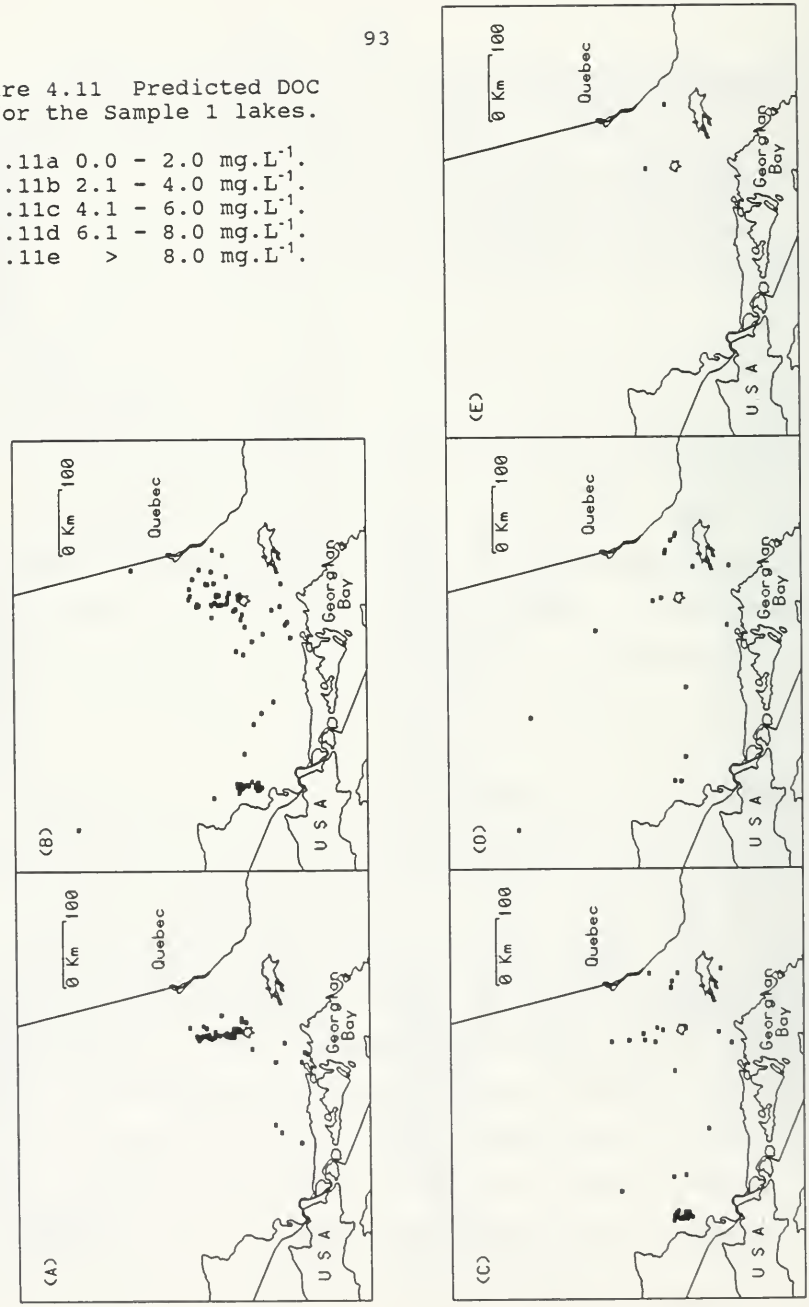
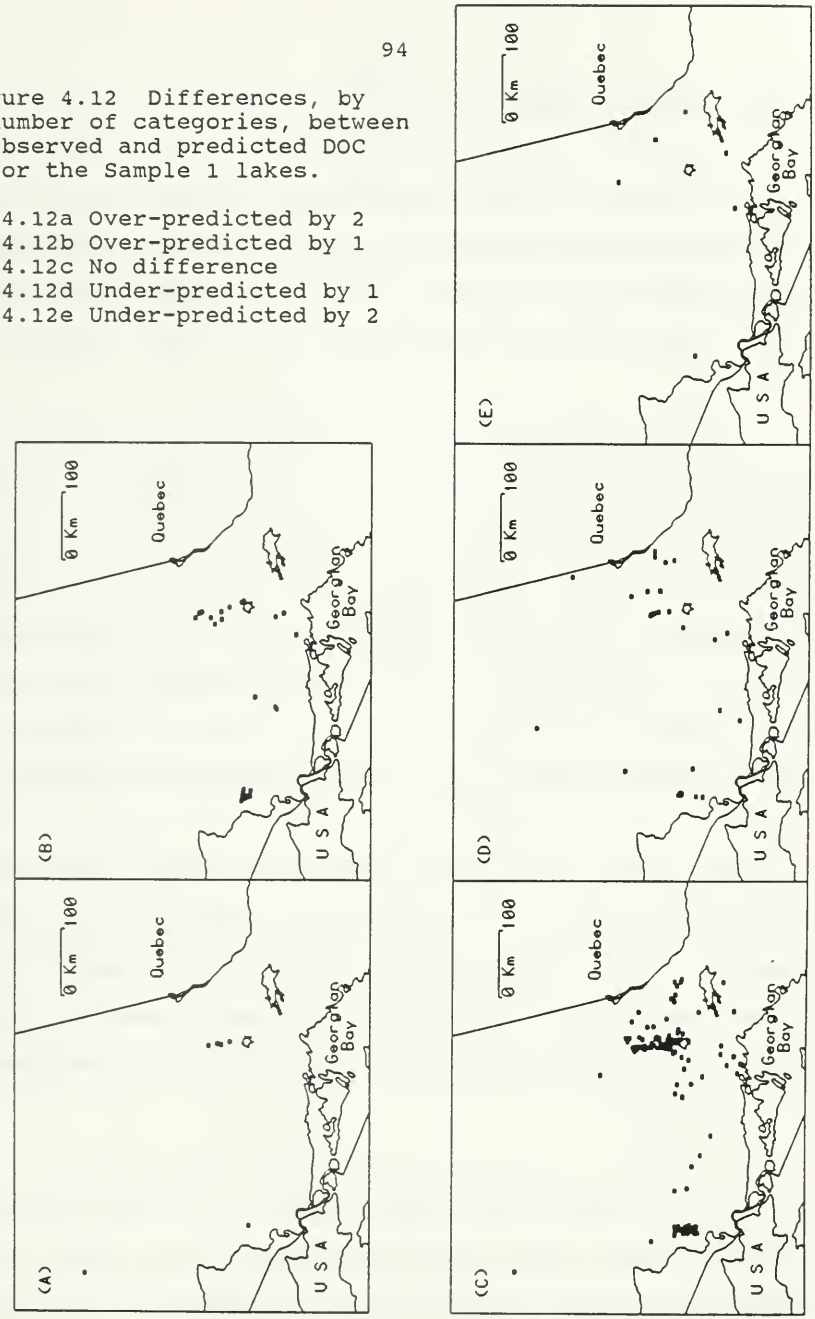


Figure 4.12 Differences, by number of categories, between observed and predicted DOC for the Sample 1 lakes.

4.12a Over-predicted by 2
4.12b Over-predicted by 1
4.12c No difference
4.12d Under-predicted by 1
4.12e Under-predicted by 2



4.4.3 Raster Mapping

The second form of mapping to be illustrated is referred to as **raster** (pixel) mapping. This type of mapping follows more logically from Landsat image data which itself is in a raster format (see Section 1.2, p. 6).

To prepare these maps, a FORTRAN program was written by the author to compute the DOC class, on a pixel-by-pixel basis, for all of the water bodies in the Landsat study images. The same bitmaps as employed earlier plus hundreds of additional masks were then used to determine the median of the classified DOC pixels for each bitmap. This value was assigned to all pixels under the respective bitmap (i.e lake) using EASI/PACE image analysis software (PCI 1989).

The PCI databases were then transformed into computer files that could be used by the raster-based GIS system known as IDRISI (Eastman 1990). Using IDRISI, the classified images were displayed and then stored with a screen-capture utility in a format that could be printed by a laser printer.

To illustrate this form of map, two Landsat quadrants have been used. The first is referred to as 19-27CD, which forms the central core of Scene 1 (see Figure 2.3, p. 31);

the second is referred to as 18-28C, the lower, left-hand quadrant of Scene 8 (Figure 2.3). As with the maps in Figures 4.9 to 4.12, lack of colour and the scale of these maps (which prevents the use of different symbols) for this report necessitates separation into maps of various DOC categories.

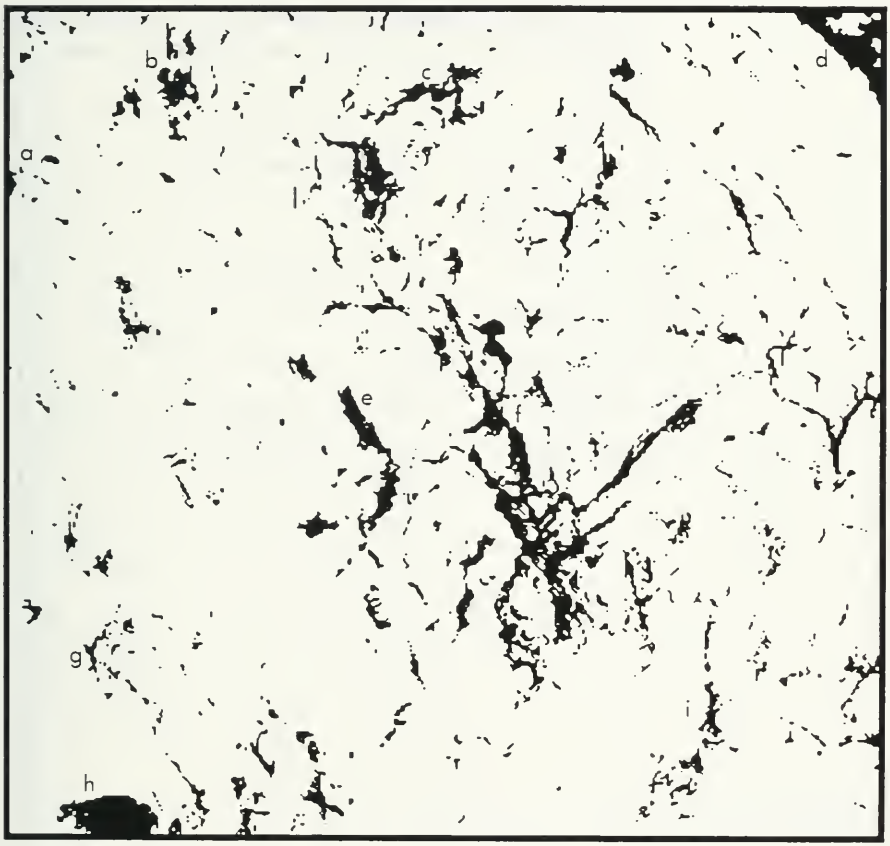
Figure 4.13a provides a view of the lakes in the Temagami area (19-27CD), including a large proportion of the sites north of Lake Wamapitei that were surveyed for this project in 1986, for which lake bitmaps were generated. The subsequent series of maps (Figures 4.13b to 4.13f) separates those lakes by DOC categories.

Similarly, Figure 4.14a provides a view of the lakes in the area south of Lake Nipissing and just north of Dorset (extending from Georgian Bay on the west to Bernard Lake in the east) for which lake bitmaps were generated. The following series of maps (Figures 4.14b to 4.14f) again separates those lakes into the five DOC categories that have been used throughout this section of the report.

These raster-based maps allow for the identification of specific lakes more readily than do the point maps provided in the previous section, as the scale of all of the maps does not lend itself to labels. However, one must do this

by using lake shape and an accompanying topographic map. To assist in this process, some of the more easily identifiable lakes have been numbered and tabulated for the maps on and following Figures 4.13a and 4.14a, respectively.

Figure 4.13a Location of classified lakes in Image 19-27CD. (See overleaf for the lakes that have been identified by letter).



The list below gives the names of a number of lakes located in Fig. 4.13a. The latitude and longitude coordinates are as given in the gazetteer for Ontario (CPCGN 1988)

a) Sunnywater (47° 24′ 80° 37′) to the east and Smoothwater (47° 24′ 80° 41′) to the south and west along the border of the map.

b) Makobe (47° 26′ 80° 25′)

c) Lady Evelyn (47° 20′ 80° 10′)

d) Timiskaming

e) Obabika (47° 5′ 80° 17′)

f) Temagami (47° 0′ 80° 3′)

g) Chiniguchi (46° 57′ 80° 42′)

h) Wanapitei (46° 45′ 80° 45′)

i) Red Cedar (46° 45′ 79° 54′)

Figure 4.13b Image 19-27CD predicted DOC: 0.0 - 2.0 $mg.L^{-1}$.

Figure 4.13c Image 19-27CD predicted DOC: 2.1 - 4.0 $mg.L^{-1}$.

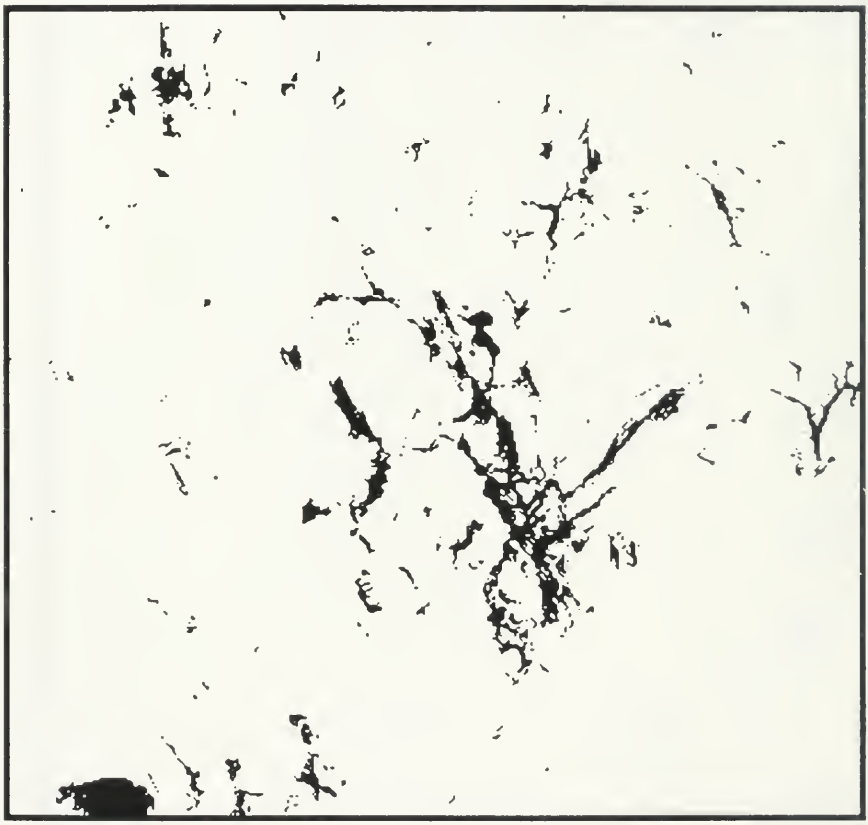
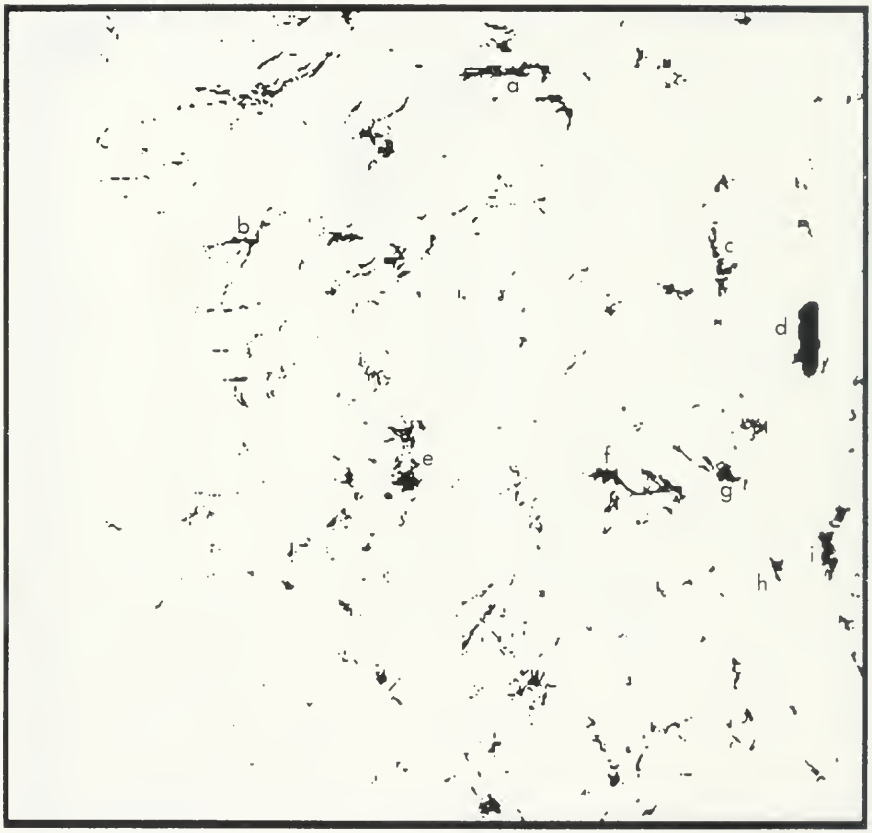


Figure 4.13d Image 19-27CD predicted DOC: 4.1 - 6.0 $mg.L^{-1}$.

Figure 4.13e Image 19-27CD predicted DOC: 6.1 - 8.0 $mg.L^{-1}$.

Figure 4.13f Image 19-27CD predicted DOC: > 8.0 $mg.L^{-1}$.

Figure 4.14a Location of classified lakes in Image 18-28C. (See overleaf for the lakes that have been identified by letter).



The list below gives the names of a number of lakes located in Fig. 4.14a. The latitude and longitude coordinates are as given in the gazetteer of Ontario (CPCGN 1988)

a)	Restoule	(46° 3′ 79° 46′)
b)	Dollars	(45° 56′ 80° 13′)
c)	Eagle	(45° 50′ 79° 30′)
d)	Bernard	(45° 45′ 79° 23′)
e)	Wahwashkesh	(45° 43′ 80° 2′)
f)	Ahmic	(45° 37′ 79° 42′)
g)	Cecebe	(45° 39′ 79° 34′)
h)	Rainy	(45° 32′ 79° 30′)
i)	Doe	(45° 32′ 79° 24′)

Figure 4.14b Image 18-28C predicted DOC: 0.0 - 2.0 $mg.L^{-1}$.

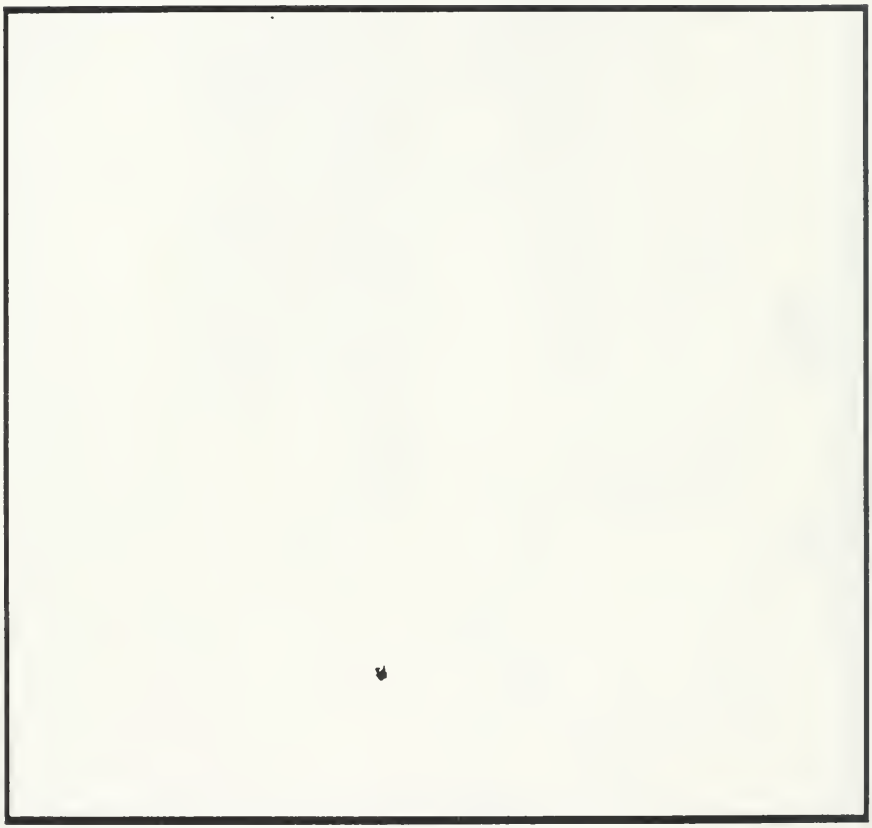


Figure 4.14c Image 18-28C predicted DOC: 2.1 - 4.0 $mg.L^{-1}$.

Figure 4.14d Image 18-28C predicted DOC: 4.1 - 6.0 $mg.L^{-1}$.

Figure 4.14e Image 18-28C predicted DOC: 6.1 - 8.0 $mg.L^{-1}$.

Figure 4.14f Image 18-28C predicted DOC: > 8.0 $mg.L^{-1}$.

It has been shown previously that in the Temagami image area (Figure 4.13, Table 4.9), more than 90% of the study lakes fall within the same observed/predicted DOC category, ± one category. A check on the Dorset image (Figure 4.14) has been more difficult because of the lack of lakes with DOC measurements (i.e. in the project database). However, the DOC values for 17 lakes were supplied after the maps in Figure 4.14 were produced (W. Keller, personal communication). These lakes, surveyed in the years from 1982 to 1990, allow a partial testing in this "blind" area.

The Landsat-DOC predictions tended to over-predict this small group of lakes when using the 2 $mg.L^{-1}$ categories. There were no observed/predicted category differences for 47% of the lakes, but an additional 47% and 6% of the lakes were over-predicted by one and two categories, respectively. On a more positive note, four of the lakes employed in the Lakeshore Capacity Study (Dillon et al. 1986) were also included in the present study, located in the 18-28D image that is not shown here. Each of them was correctly characterized using the Landsat-DOC regression models in terms of their concentrations of dissolved organic carbon.

To further assess the DOC predictions, an analysis of the **absolute** differences between observed and predicted values was undertaken. As the 2 $mg.L^{-1}$ DOC classes are

arbitrary but necessary for mapping purposes, it could be argued that they are inappropriate (i.e. a lake with observed and predicted DOC of 1.9 and 2.1 $mg.L^{-1}$, respectively, would be considered "misclassified").

Table 4.11 shows that this may well be the case. The DOC concentrations of by far the majority of the study lakes and even the 17 lakes in the Dorset area have been predicted within 1.0 to 1.5 $mg.L^{-1}$. The table also suggests, however, that when using Landsat data for water quality predictions that image-by-image regression models may be necessary.

Table 4.11 Cumulative percentages of lakes by **absolute** differences between observed and predicted DOC ($mg.L^{-1}$).

Absolute Difference Categories	N.E. Ontario (n=230)	"Temagami" 19-27CD (n=81)	"Algoma" 22-27 (n=51)	"Dorset" 18-28C (n=17)
0.0 - 0.5	48.5	54.3	43.1	35.3
0.6 - 1.0	73.6	85.2	72.5	52.9
1.1 - 1.5	84.6	93.8	84.3	76.4
1.6 - 2.0	89.0	93.8	92.2	82.3
2.0 - 2.5	91.2	95.1	92.2	94.1
> 2.0	100.0	100.0	100.0	100.0
Mean Absolute Difference ($mg.L^{-1}$)	0.97	0.62	0.98	1.11

4.5 Applications To Consider

In the most recent published paper on the use of Landsat imagery for water resources assessment in Canada, Wickware et al. (1991) report significant progress in using satellite data to map the locations and determine the surface areas of lakes. They argue that "counts and measures information constitutes an integral part of ongoing modelling efforts to describe and predict the effects of acidification on surface waters" (Wickware et al. 1991, p. 57). The utility of "counts and measures" information can certainly be seen in the summary of the acidification of Ontario lakes provided by Neary et al. (1990), a publication that has proved to be of great benefit in the preparation of the present report.

While in full support of this view, the results of the this research project indicate that the "counts and measures" stage of investigation can be extended to one of water quality assessment using remotely sensed data. If Landsat data can be used to predict DOC with reasonable accuracy and if DOC can be used as a surrogate measure of other lake parameters, then Landsat data should be used as a water quality monitoring tool. It has been demonstrated that 60% to 65% of the study lakes can be accurately classified into their proper DOC category, while 91% to 95%

of the lakes can be identified correctly, ± 1 DOC category.

Numerous possibilities for lake water quality monitoring or mapping can be suggested given the success of these predictions. The two that have been the focus of this paper, lake acidity and trophic status, are briefly discussed below as a means to suggest work to be undertaken in the future.

Lake Acidity

In their tabulation of data on the sensitivity of Ontario lakes to acidification, the M.O.E. (1983) included the following water chemistry variables: pH, conductivity, colour, alkalinity, and calcium. Alkalinity is further highlighted by being used to group Ontario lakes by degrees of sensitivity using the following classes defined by ranges of alkalinity ($\mu eq.L^{-1}$): acidified lakes, ≤ 0; extreme sensitivity, 0 - 40; moderate sensitivity, 40 - 200; low sensitivity, 200 - 500; and not sensitive, > 500.

If we consider these variables as some of the most significant water chemsitry parameters in studies of lake acidity, how can the Landsat DOC maps assist with the inventorying and monitoring of lake acidity in Ontario? Indeed, how can the DOC maps be of assistance when it has already been demonstrated (Section 4.3 and Appendix C) that

the correlations between DOC (observed or predicted) and these parameters are not particularly high?

As an example, let us consider alkalinity. This is "a measure of the acid neutralizing capacity of an aquatic ecosystem" (M.O.E. 1983, p. i). Yet, "knowing the alkalinity of a given lake, the state of the biota of that lake may be predicted from measurements of lakes where intensive biological surveys have been performed. This assessment will expectably be wrong in some individual lakes." (M.O.E. 1983, p. iii, my underlining). Alkalinity is NOT perfectly correlated with pH! In the present survey area, the correlation between pH and TIP alkalinity is equal to 0.56 ($P < 0.01$, $n = 519$). For the lakes of the Temagami (Figure 4.13) and the Dorset areas (Figure 4.14), the pH and alkalinity relationships are 0.87 ($P < 0.01$, $n = 101$) and 0.82 ($P < 0.01$, $n = 22$), respectively.

Variations exist between the pH and alkalinity association both within- and between-regions (see Tables 4.12 to 4.14). Similar variation exists between pH-DOC and alkalinity-DOC associations. For these associations, descriptive statistics are provided for pH (Tables 4.15 to 4.17) and alkalinity (Tables 4.18 to 4.20) by predicted DOC categories.

Table 4.12 Mean pH values by alkalinity-defined lake sensitivity classes for the entire study area.

Class	Minimum	Maximum	Mean	n
Acidified	4.12	5.51	4.91	90
Extreme Sensitivity	4.95	6.70	5.86	113
Moderate Sensitivity	5.83	7.70	6.72	217
Low Sensitivity	6.50	7.80	7.25	60
Not Sensitive	6.35	8.20	7.52	39

Table 4.13 Mean pH values by alkalinity-defined lake sensitivity classes for the Temagami area (Figure 4.13).

Class	Minimum	Maximum	Mean	n
Acidified	4.34	5.51	4.87	45
Extreme Sensitivity	5.49	6.39	5.87	28
Moderate Sensitivity	6.44	7.20	6.82	14
Low Sensitivity	6.65	7.53	7.23	14
Not Sensitive	-	-	-	-

Table 4.14 Mean pH values by alkalinity-defined lake sensitivity classes for the Dorset area (Figure 4.14).

Class	Minimum	Maximum	Mean	n
Acidified	4.75	4.75	4.75	1
Extreme Sensitivity	5.62	6.32	5.97	2
Moderate Sensiivity	6.07	7.05	6.54	14
Low Sensitivity	6.80	7.61	7.18	5
Not Sensitive	-	-	-	-

Table 4.15 Mean pH values by predicted DOC classes ($mg.L^{-1}$) for the entire study area.

Class	Minimum	Maximum	Mean	n
0.0 - 2.0	4.10	8.00	5.59	90
2.1 - 4.0	4.51	8.20	6.35	193
4.1 - 6.0	4.74	7.75	6.51	135
6.1 - 8.0	4.46	7.96	6.75	73
> 8.0	4.79	7.75	6.81	30

Table 4.16 Mean pH values by predicted DOC classes ($mg.L^{-1}$) for the Temagami study area (Figure 4.13).

Class	Minimum	Maximum	Mean	n
0.0 - 2.0	4.34	7.26	5.08	40
2.1 - 4.0	4.58	7.37	6.11	45
4.1 - 6.0	5.06	7.53	6.35	7
6.1 - 8.0	5.82	7.03	6.54	6
> 8.0	5.49	6.99	6.09	3

Table 4.17 Mean pH values by predicted DOC classes ($mg.L^{-1}$) for the Dorset study area (Figure 4.14).

Class	Minimum	Maximum	Mean	n
0.0 - 2.0	6.36	6.36	6.36	1
2.1 - 4.0	6.80	6.80	6.80	1
4.1 - 6.0	4.75	7.20	6.38	10
6.1 - 8.0	5.62	7.61	6.73	9
> 8.0	6.66	6.66	6.66	1

Table 4.18 Mean TIP alkalinity values ($\mu eq.L^{-1}$) by predicted DOC classes ($mg.L^{-1}$) for the entire study area.

Class	Minimum	Maximum	Mean	n
0.0 - 2.0	-88	2332	50	90
2.1 - 4.0	-37	1776	104	193
4.1 - 6.0	-17	1294	146	135
6.1 - 8.0	-29	3606	296	73
> 8.0	-18	1318	426	13

Table 4.19 Mean TIP alkalinity values ($\mu eq.L^{-1}$) by predicted DOC classes ($mg.L^{-1}$) for the Temagami study area (Figure 4.13).

Class	Minimum	Maximum	Mean	n
0.0 - 2.0	-49	209	-7	40
2.1 - 4.0	-28	320	64	45
4.1 - 6.0	-8	347	127	7
6.1 - 8.0	9	310	142	6
> 8.0	4	132	51	3

Table 4.20 Mean TIP alkalinity values ($\mu eq.L^{-1}$) by predicted DOC classes ($mg.L^{-1}$) for the Dorset study area (Figure 4.14).

Class	Minimum	Maximum	Mean	n
0.0 - 2.0	73	73	73	1
2.1 - 4.0	218	218	218	1
4.1 - 6.0	-17	397	115	10
6.1 - 8.0	11	332	153	9
> 8.0	136	136	136	1

Despite the lack of an adequate sample size for some of these tables, it is clear that there are trends or critical cutoff points in the associations of these lake parameters even though correlation coefficients tell us to be cautious. Tables 4.12 to 4.20 and the histograms in Appendix A for pH (A-3), TIP alkalinity (A-4), conductivity (A-4), and calcium (A-7) would suggest that the 0.0-2.0 $mg.L^{-1}$ DOC mapping class be the focus if the intent is to examine lake acidity. It is highly probable that this mapping class is dominated by lakes with low values for these parameters.

The remaining DOC mapping classes would also be useful for lake acidification studies given the relationships between DOC and lake clarity (as measured by Secchi disc depth) and colour (apparent colour in hazen units), and in turn, the observations that acidic lakes on the Precambrian Shield tend to have high Secchi and low colour values.

For the entire study area the mean values for Secchi depth (m) for each of the five predicted DOC classes are: 8.8, 5.6, 3.7, 3.3, 2.1, respectively. The Secchi values for the lakes of the 19-27CD or Temagami image area are, respectively: 8.7, 6.1, 4.4, 3.6, 2.1. Similarly, for the entire study area the mean values for apparent colour (hz) for each of the five predicted DOC classes are: 3.5, 10.2, 23.4, 31.8, 46.0, respectively. The colour values for the

19-27CD or Temagami image area lakes are, respectively: 3.4, 5.4, 19.3, 26.2, and 15.4.

By contrast, average Secchi depth and apparent colour values for the 18-28C image area lakes show little variation between predicted DOC mapping classes, ranging from 3.2 to 3.8 m for Secchi depth and from 24.1 to 33.8 hz for apparent colour. Clearly, there are regions in the province where these lake parameters are not driven or associated particularly well with dissolved organic carbon. In these areas the Landsat-DOC mapping may be perfectly adequate but may not be used to predict lake acidity characteristics.

Of particular relevance to Sudbury-area studies of lake acidification are the concentrations of sulphate. For the lakes of the 19-27CD image, variations in sulphate concentrations ($mg.L^{-1}$) are associated with the five predicted DOC-classes with mean values as follows: 11.4, 11.9, 10.4, 9.8, 9.2. The dataset currently available for this image area is dominated by lakes from the "Sudbury sulphur zone". This can be seen by the significantly greater differentiation by predicted-DOC classes when all lakes in the project dataset are used. For this larger group of lakes the repective mean values are: 12.1, 10.0, 7.8, 7.6, and 6.9 $mg.L^{-1}$. In the currently small sample of lakes for the 18-28C or Dorset image area (SO4 values for

only 18 lakes), there is again little variation in sulphate concentrations with values ranging from 7.0 to 8.1 $mg.L^{-1}$.

Given the cautionary remarks above, it was particularly gratifying to see that in the Dorset image (Figure 4.14b), Round Lake stands out prominently. Data for 1981 (Pitblado and Keller 1984) indicated that this lake had low pH (5.06), low alkalinity (-0.43 $mg.L^{-1}$), low colour (1.3 hz), and high Secchi depth (7.5 m). The sulphate concentration of Round lake was not particularly high in 1981 (6.5 $mg.L^{-1}$) and in fact decreased to 5.8 $mg.L^{-1}$ in 1983 (Pitblado and Keller 1984). And only slight variations over that two-year period occurred for the other water chemistry parameters listed above.

Trophic Status

Of itself, dissolved organic carbon is a useful water quality parameter to have available when assessing the trophic status of lakes (Dillon et al. 1986). As with lake acidification studies, however, DOC or the Landsat-DOC predictions become even more useful when other water parameters can be estimated which are also relevant to trophic status analyses (see Appendices A, B, and C). Some of these, colour and Secchi depth, have already been demonstrated.

Other relevant water chemistry variables of interest here that have been found to be associated with the predicted-DOC classes are chlorophyll *a*, total Kjeldahl nitrogen, and total phosphorus. Table 4.21 provides a summary of the mean values for these parameters, again for the entire study area and for the two image areas that have been used as examples in this section of the report and in Section 4.3.

Dillon et al. (1986) have outlined some of the difficulties in defining the trophic status for lakes (see also Section 1.3) and the variations that arise when using different trophic state indicators. Recognizing these limitations, all of the relationships shown here are consistent in terms of their trends. Secchi depth decreases as there is an increase in predicted-DOC category; while apparent colour, chlorophyll *a*, total Kjeldahl nitrogen, and total phosphorus increase with increasing predicted-DOC category. These trends are similar to those shown by the histograms of Appendix A and the correlation coefficients tabulated in Appendix C.

As a final comment for this section of the report, it is useful to reflect on the statement by Dillon et al. (1986, p. 1) that "It is well-known that phosphorus, the algal nutrient present in shortest supply, controls the

Table 4.21 Mean values for selected water chemistry variables by predicted-DOC classes ($mg.L^{-1}$).

Predicted DOC Classes	Entire Study Area	19-27CD Temagami	18-28C Dorset
Chlorophyll *a* ($\mu g.L^{-1}$)			
0.0 - 2.0	0.56	0.58	-
2.1 - 4.0	1.79	1.38	-
4.1 - 6.0	2.20	1.38	-
6.1 - 8.0	1.53	1.35	-
> 8.0	1.85	2.00	-
Total Kjeldahl N ($\mu g.L^{-1}$)			
0.0 - 2.0	111	103	-
2.1 - 4.0	201	159	-
4.1 - 6.0	281	192	358
6.1 - 8.0	290	208	307
> 8.0	339	257	420
Total P ($\mu g.L^{-1}$)			
0.0 - 2.0	4.27	4.03	-
2.1 - 4.0	6.20	5.00	-
4.1 - 6.0	8.33	5.57	10.6
6.1 - 8.0	9.41	7.75	10.9
> 8.0	11.25	8.00	14.0

trophic status of most Precambrian lakes because of its relationship with algal biomass and production". Yet this indicator of trophic state seems to have no indicator for itself.

Working with the current dataset that includes 325 lakes well-distributed throughout the study area, the two variables that are most highly correlated with Total P are total Kjeldahl N ($r = 0.71$, $P < 0.01$; and $r = 0.73$, $P < 0.01$ when both Total P and total Kjeldahl N are log-transformed) and predicted dissolved organic carbon ($r = .67$, $P < 0.01$ when both are log-transformed). And as illustrated in Appendix C, of all the water chemistry variables employed in this study it is total Kjeldahl N that is most highly correlated with the Landsat-predicted DOC values.

If Total P cannot be measured in the field, then Landsat data holds the possibility of its "measurement" by exploiting this triumvarate of trophic state indicators.

5. Temporal Analyses of Bowland Lake

5.1 Introduction

In August of 1983 Bowland Lake was treated with $CaCO_3$ as part of a long-term programme to investigate the feasibility of using neutralization as a means of protecting and rehabilitating Ontario lakes which receive high inputs of acid deposition (Keller et al. 1990). If the changes in the surface water characteristics that were induced by this treatment include parameters of optical significance, then it might be possible to observe those changes using remotely sensed data.

Bowland Lake is located 70 km north (47°5'N, 80°50'W) of Sudbury. It has a surface area of 109.4 ha and its N-S/E-W orientation and configuration is as shown in Figure 5.1. Prior to treatment the mean pH was 4.9. Soon after neutralization, values of whole-lake pH exceeded 6.0, reaching a maximum of 6.7 by the summer of 1984 (Molot et al. 1990).

In addition to pH alterations, Molot et al. (1990) have provided evidence of statistically significant increases in dissolved organic carbon. They also speculated that the

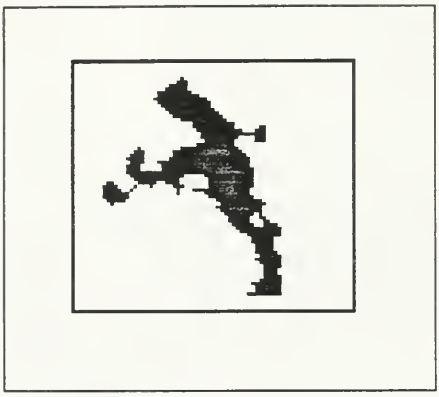


Figure 5.1 Bowland Lake, Landsat TM4

change in DOC could have accounted for the decrease in Secchi disc depth from a mean of 7.8 m (pre-neutralization period June 1982 - July 1983) to a mean of 5.4 m (post-neutralization period May 1984 - October 1985). At the same time, Al declined from pre-neutralization levels of 130-140 $\mu g.L^{-1}$ to 30 $\mu g.L^{-1}$ in 1985, perhaps further evidence in support of the Al-DOC-tranparency link discussed by Effler et al. (1985). It must be noted, however, that the differences in DOC reported by Molot et al. (1990) are considered here to have been relatively subtle. In the upper strata of the lake, the mean concentrations of DOC increased from 2.0 $mg.L^{-1}$ (June 1982 - July 1983; standard deviation of 0.4) to 2.5 $mg.L^{-1}$ (August 1983 - October 1985; standard deviation of 0.5).

It is clear that neutralization has, among other things, altered the optical characteristics of Bowland Lake. What is not so clear is whether Landsat TM has the resolution capable of detecting these changes.

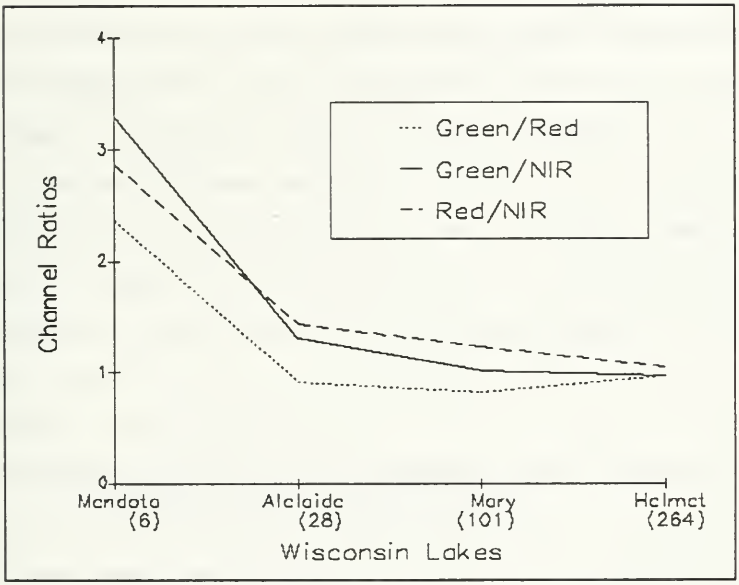
In terms of a technique to analyze these changes, the remote sensing literature is not particularly helpful as most water quality studies have been of a spatial nature rather than temporal. As well, the Landsat data available for this analysis are derived from two sensors (MSS and TM) carried on board four different satellites in the Landsat programme (see Section 2.3). However, temporal analyses of terrestrial targets have made extensive use of channel ratios as a means to compare data from different times and different satellites (see, for example, the vegetation distribution and change detection studies for the Sudbury area: Pitblado and Amiro 1982; Allum and Dreisinger 1986). The use of channel ratios has met with some success for water quality analyses (Piech et al. 1978; Jerome et al. 1989), but Novo and Godoy, Jr. (1989) were unable to detect trophic level changes in a Brazilian reservoir for the period from 1984 to 1988 using TM reflectance ratios.

Adoption of channel ratios for water quality assessments is often dependent on the availability of reflectance data from the blue and green portions of the

electromagnetic spectrum (Piech et al. 1978). An analysis of blue-green ratios is not possible for the study of Bowland Lake as the majority of the Landsat data available was derived from the MSS which has no blue band. Given this limitation, what can be expected from the ratios that can be computed? Looking back at Figure 4.1, it is apparent that there are significant differences in the absorption of green and red light as the DOC-colour of lake waters increases, but little difference as one approaches and enters the area of near-infrared (NIR).

A re-working of the values provided by Wetzel (1975) produces the plots shown in Figure 5.2. Three ratios have been computed for each of the four lakes: Green/Red, Green/NIR, and Red/NIR. Imagine that these four lakes are instead just one lake in which we observe an increase in DOC-colour over time (i.e. from Mendota to Helmet). As the DOC-colour increases, the ratios decrease. The most significant decrease occurs between very clear water conditions to moderately coloured and then flattens out in highly coloured waters even when the DOC-colour increase is substantial.

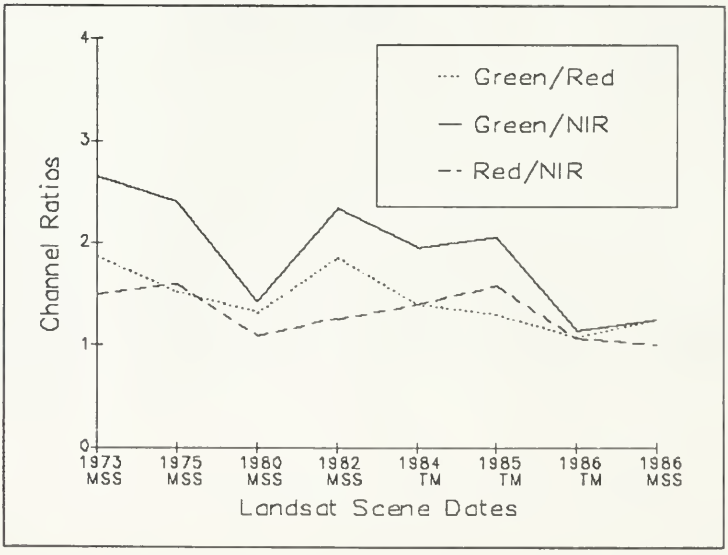
Figure 5.2 Reflectance ratios for Wisconsin lakes of increasing colour (data computed from Wetzel 1975).



5.2 Changes in Spectral Response Over Time

Channel ratios for Bowland Lake were computed from five Landsat MSS images (1973, 1975, 1980, 1982, 1986) and three Landsat TM images (1984, 1985, 1986). The Landsat channels that were employed are as follows (see Table 1.1 for the wavelength limits in μm): for the Green/Red ratios - MSS1/MSS2, TM2/TM3; for the Green/NIR ratios - MSS1/MSS4, TM2/TM4; and for the Red/NIR ratios - MSS2/MSS4, TM3/TM4. Plots of these ratios over time (Figure 5.3) provide

Figure 5.3 Reflectance ratios for Bowland Lake for selected Landsat images from 1973 to 1986.



tantalizing evidence that the Landsat sensors are recording changes in reflectance over the period from 1973 to 1986.

As one would hope, the reflectance ratios decrease over time as the pH and DOC increase and the Secchi disc depth decreases (Molot et al. 1990). A significant dip in the reflectance ratio lines plotted in Figure 5.3 occurs for the 1980 MSS image. This can be accounted for by the fact that the entire image on that date is dominated by haze. Atmospheric problems also were encountered with the 1986 images (MSS and TM). But in the latter case, the cumulus clouds and cloud shadows are spatially discrete so "contaminated" pixels could be removed (see Figure 5.4e).

To examine the statistical characteristics of this series of ratios, linear correlation coefficients were computed relating time with the mean values of the ratios for the images. As well, discriminant classifications were undertaken using the three computed reflectance ratios and condidering the pixels of each image date as a "group". These analyses were done by selectively including or excluding various images over the 1973 to 1986 period.

When all eight images of Bowland Lake are included, a discriminant classification accuracy of 65.9% is achieved for the pixels grouped by image date. Linear correlation

coefficients confirm the trend (i.e. decreasing ratio values over the period 1973 to 1986) suggested in a visual inspection of Figure 5.3. The r values for this analysis are: Green/Red ratios, -0.72 ($P < 0.05$); Green/NIR ratios, -0.75 ($P < 0.05$); Red/NIR, -0.54 which was not statistically significant ($P > 0.05$).

This may not be considered a fair comparison as that series includes the haze-affected 1980 MSS image and two 1986 images (MSS and TM). When the 1980 image is removed and alternately the 1986 MSS then the 1986 TM images, the discriminant classification accuracies increase marginally: 67.3% with the 1986 TM image and 66.2% with the 1986 MSS image. The related correlation coefficients, many of which are not statistically significant, continue to show the trend in decreasing reflectance ratios (in the order, Green/Red, Green/NIR, Red/NIR): -0.80 ($P > 0.05$), -0.88 ($P < 0.05$), -0.55 ($P > 0.05$) when the 1986 TM image is included; and, -0.77 ($P > 0.05$), -0.94 ($P < 0.01$), -0.64 ($P > 0.05$) when the 1986 MSS image is included.

A fairer comparison might be made when separately comparing the MSS and TM images. As shown in Table 5.1 and Table 5.2, there is a good deal of overlap in the reflectance ratios from image to image both for the MSS and the TM data. Even so, the separation of the images is

Table 5.1 Discriminant classification results based on channel ratios for four selected Landsat MSS scenes for Bowland Lake.

Actual Group	(n)	Predicted Group 1	2	4	8
Group 1 1973 MSS	167	70 41.9%	13 7.8%	84 50.3%	0 0.0%
Group 2 1975 MSS	197	14 7.1%	152 77.2%	16 8.1%	15 7.6%
Group 4 1982 MSS	155	10 6.5%	24 15.5%	121 78.1%	0 0.0%
Group 8 1986 MSS	89	0 0.0%	0 0.0%	0 0.0%	89 100.0%

Table 5.2 Discriminant classification results based on channel ratios for three selected Landsat MSS scenes for Bowland Lake.

Actual Group	(n)	Predicted Group 5	6	7
Group 5 1984 TM	205	160 78.0%	45 22.0%	0 0.0%
Group 6 1985 TM	209	36 17.2%	173 82.8%	0 0.0%
Group 7 1986 TM	100	0 0.0%	0 0.0%	100 100.0%

reasonably discrete from one date to another with classification accuracies of 71.1% for the MSS dates and 84.2% for the TM dates.

Reduction of the number of image dates included in the linear correlation analysis will obviously impact on the statistical significance of the correlation coefficients. But once again the reflectance ratios generally decrease over time. With only three TM images, none of the coefficients are statistically significant ($P > 0.05$): -0.98, -0.81, -0.62 for the Green/Red, Green/NIR, Red/NIR ratios, respectively. The Landsat TM images were acquired in different months of the year (June 1984, May 1985, August 1986) while all of the MSS images were acquired in July-August. The latter (MSS) images provide a better indication of the alterations in reflectance ratios over time for Bowland Lake: -0.73 ($P > 0.05$), -0.97 ($P < 0.05$), -0.95 ($P > 0.05$) for the Green/Red, Green/NIR, Red/NIR ratios, respectively.

At this point in time, the analyses of the Bowland Lake reflectance data suggest that changes in the optical characteristics of the lake are being sensed by Landsat. But the evidence is not overwhelming. There is, for example, no sharp break in the plot of reflectance ratios (Figure 5.3) between 1982 and 1984. Yet, there is a very

significant decrease between 1985 and 1986, at a time when reacidification is taking place (Molot et al. 1990). The Landsat imagery at hand, and perhaps the field data, are insufficient to address these observations.

For purely illustrative/information purposes, maps of the Bowland MSS ratios have been provided in Figures 5.4 (Green/Red), 5.5 (Green/NIR), and 5.6 (Red/NIR). In association with the discriminant and correlation analyses outlined above, they require further analysis beyond the scope of the present project. Of particular importance for future work are the impacts on both the relative and absolute Landsat reflectance values associated with: the location of pixels vis-à-vis near-shore or lake centre; the increase in Si with neutralization (Molot et al. 1990); and, probably of great significance, the impacts associated with the elimination of filamentous algae in response to neutralization, followed by re-establishment to near preliming coverage with later reacidification (Jackson et al. (1990).

Fig. 5.4a MSS 1973

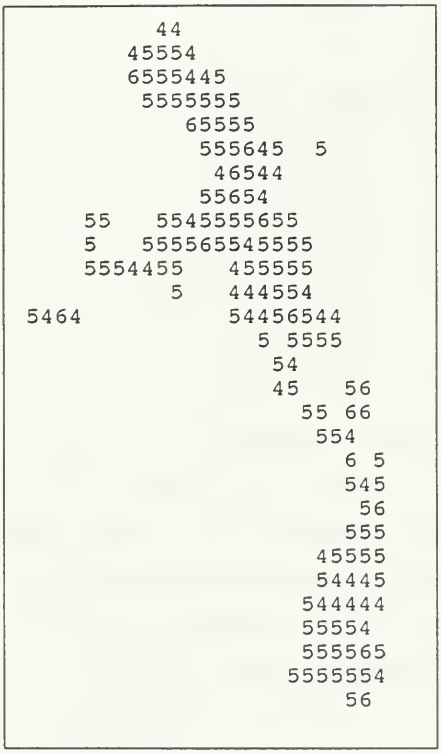


Figure 5.4

Bowland Lake

Green/Red Ratios

Map Code	Ratios Legend
1	0.76 - 1.00
2	1.01 - 1.25
3	1.26 - 1.50
4	1.51 - 1.75
5	1.76 - 2.00
6	2.01 - 2.25
7	2.26 - 2.50
8	2.51 - 2.75
9	2.76 - 3.00
#	3.01 - 3.25
@	3.26 - 3.50

Green/Red Ratios

Fig. 5.4b MSS 1975

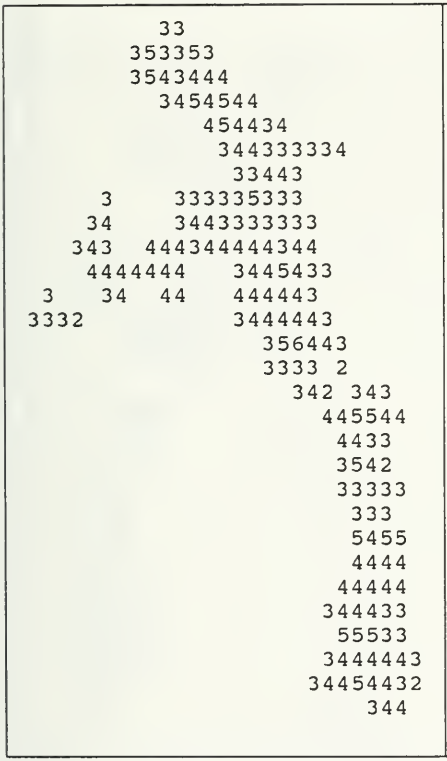
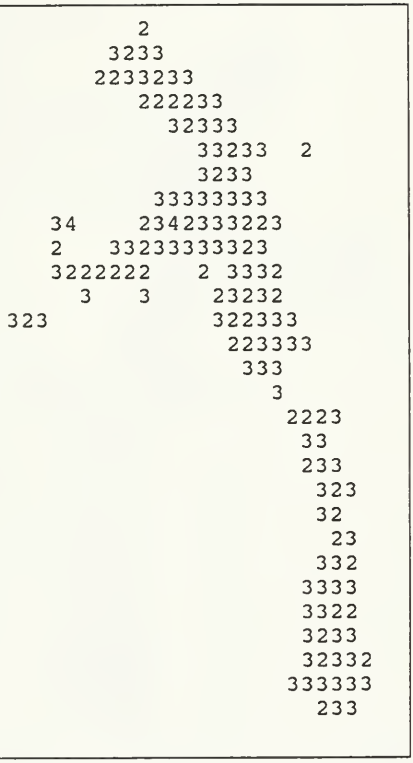


Fig. 5.4c MSS 1980



Map Code	Ratios Legend
1	0.76 - 1.00
2	1.01 - 1.25
3	1.26 - 1.50
4	1.51 - 1.75
5	1.76 - 2.00
6	2.01 - 2.25
7	2.26 - 2.50
8	2.51 - 2.75
9	2.76 - 3.00
#	3.01 - 3.25
@	3.26 - 3.50

Green/Red Ratios

Fig. 5.4d MSS 1982

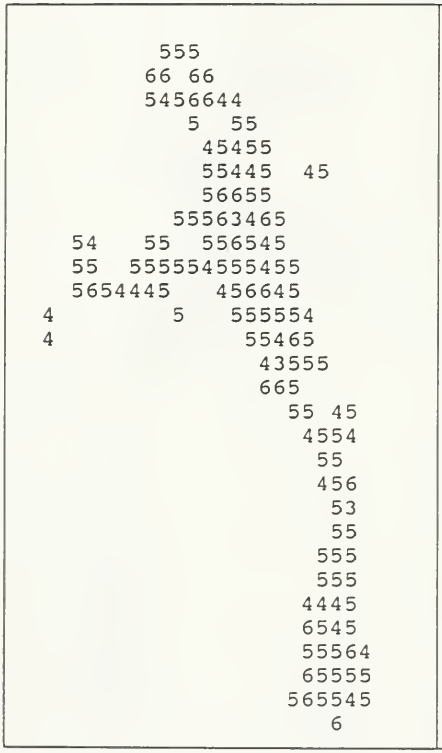
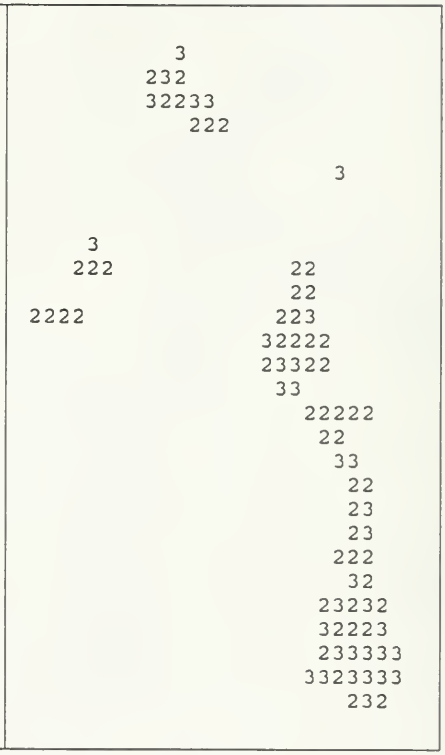


Fig. 5.4e MSS 1986



Map Code	Ratios Legend
1	0.76 - 1.00
2	1.01 - 1.25
3	1.26 - 1.50
4	1.51 - 1.75
5	1.76 - 2.00
6	2.01 - 2.25
7	2.26 - 2.50
8	2.51 - 2.75
9	2.76 - 3.00
#	3.01 - 3.25
@	3.26 - 3.50

Fig. 5.5a MSS 1973

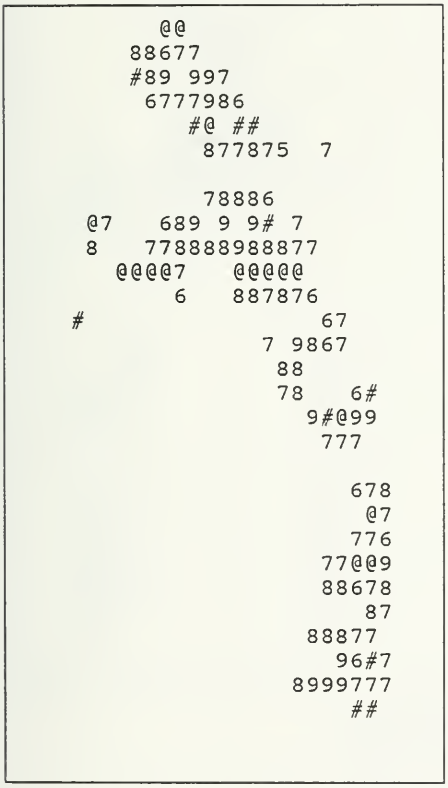


Figure 5.5

Bowland Lake

Green/NIR Ratios

Map Code	Ratios Legend
1	0.76 - 1.00
2	1.01 - 1.25
3	1.26 - 1.50
4	1.51 - 1.75
5	1.76 - 2.00
6	2.01 - 2.25
7	2.26 - 2.50
8	2.51 - 2.75
9	2.76 - 3.00
#	3.01 - 3.25
@	3.26 - 3.50

Green/NIR Ratios

Fig. 5.5b MSS 1975

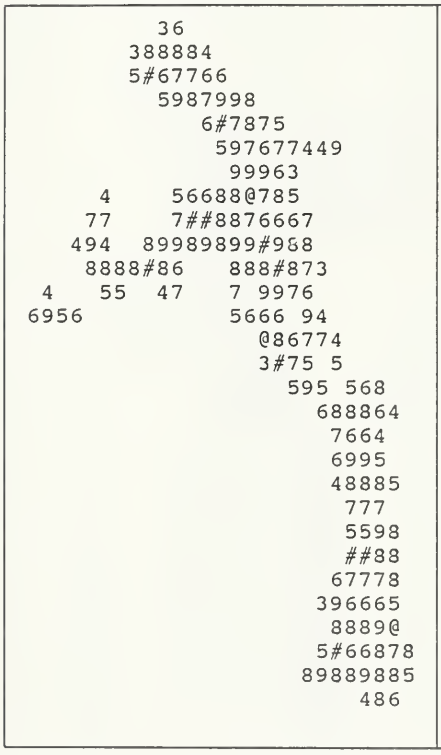
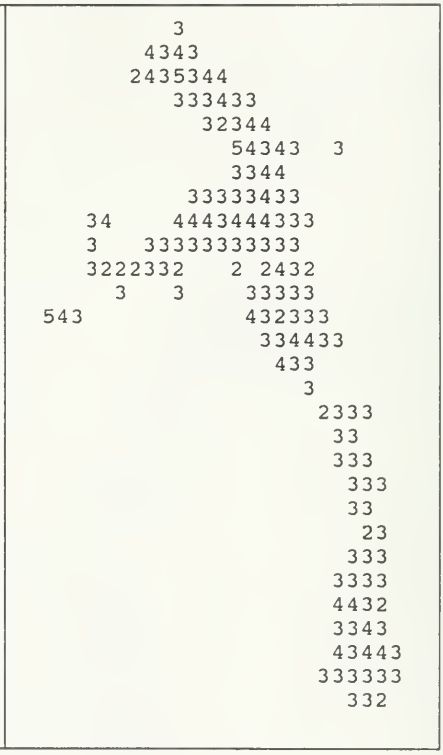


Fig. 5.5c MSS 1980



Map Code	Ratios Legend
1	0.76 - 1.00
2	1.01 - 1.25
3	1.26 - 1.50
4	1.51 - 1.75
5	1.76 - 2.00
6	2.01 - 2.25
7	2.26 - 2.50
8	2.51 - 2.75
9	2.76 - 3.00
#	3.01 - 3.25
@	3.26 - 3.50

Green/NIR Ratios

Fig. 5.5d MSS 1982

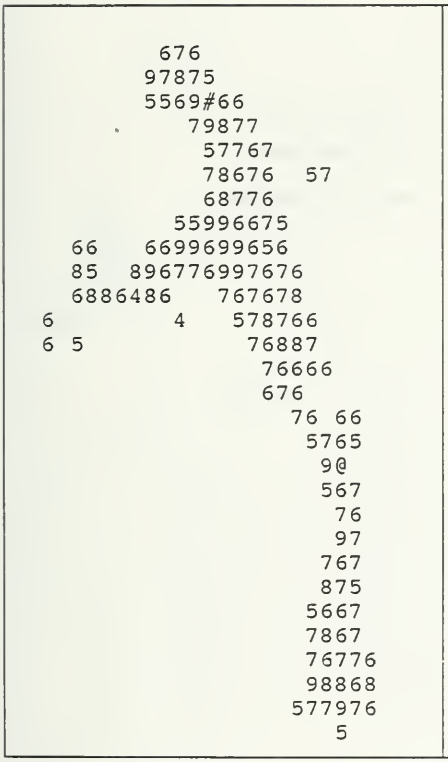
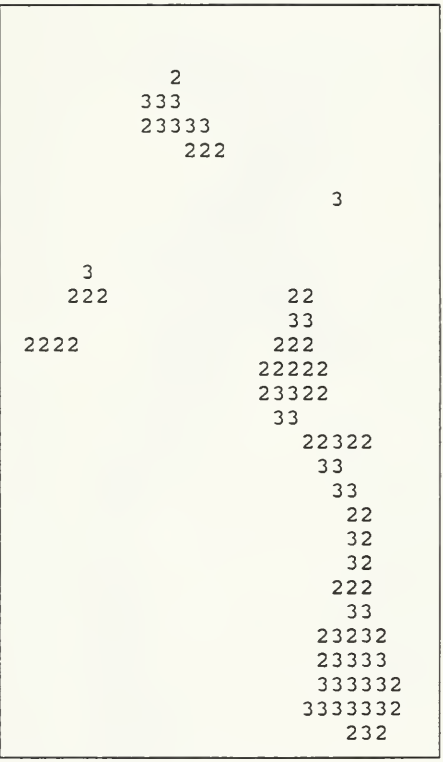


Fig. 5.5e MSS 1986



Map Code	Ratios Legend
1	0.76 - 1.00
2	1.01 - 1.25
3	1.26 - 1.50
4	1.51 - 1.75
5	1.76 - 2.00
6	2.01 - 2.25
7	2.26 - 2.50
8	2.51 - 2.75
9	2.76 - 3.00
#	3.01 - 3.25
@	3.26 - 3.50

Fig. 5.6a MSS 1973

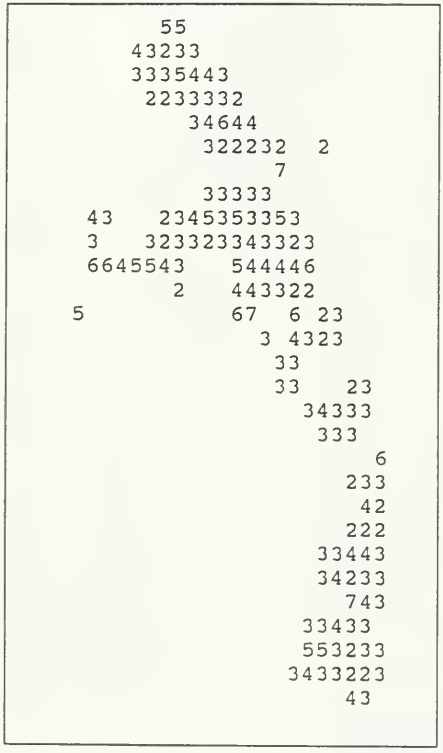


Figure 5.6

Bowland Lake

Red/NIR Ratios

Map Code	Ratios Legend
1	0.76 - 1.00
2	1.01 - 1.25
3	1.26 - 1.50
4	1.51 - 1.75
5	1.76 - 2.00
6	2.01 - 2.25
7	2.26 - 2.50
8	2.51 - 2.75
9	2.76 - 3.00
#	3.01 - 3.25
@	3.26 - 3.50

Red/NIR Ratios

Fig. 5.6b MSS 1975

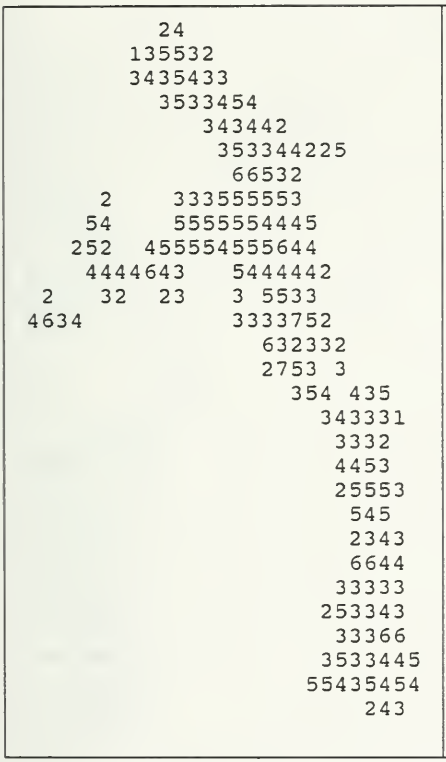
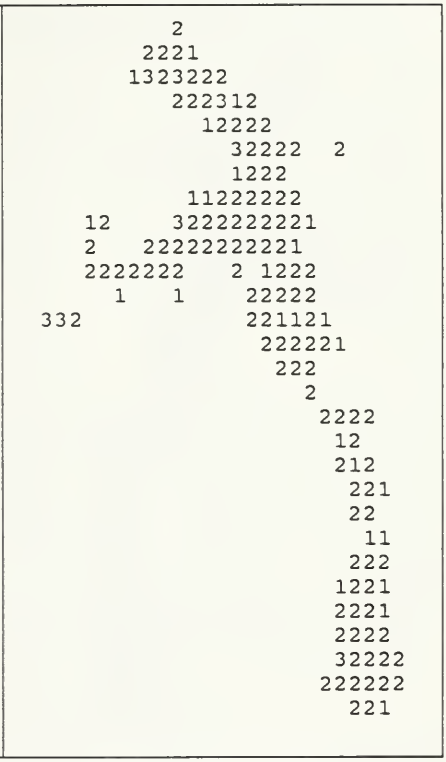


Fig. 5.6c MSS 1980



Map Code	Ratios Legend
1	0.76 - 1.00
2	1.01 - 1.25
3	1.26 - 1.50
4	1.51 - 1.75
5	1.76 - 2.00
6	2.01 - 2.25
7	2.26 - 2.50
8	2.51 - 2.75
9	2.76 - 3.00
#	3.01 - 3.25
@	3.26 - 3.50

Red/NIR Ratios

Fig. 5.6d MSS 1982

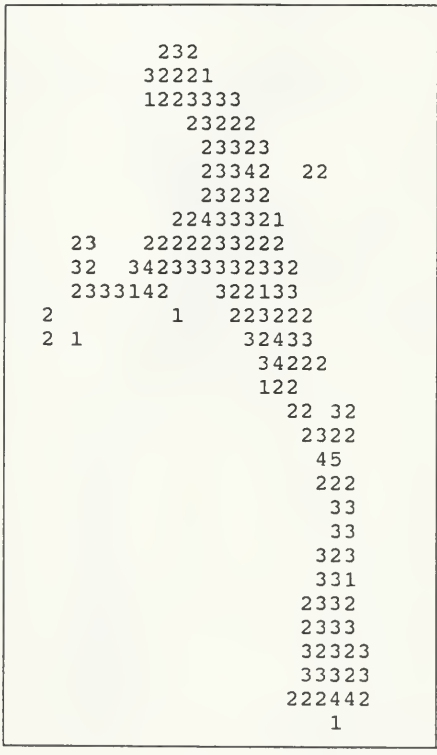
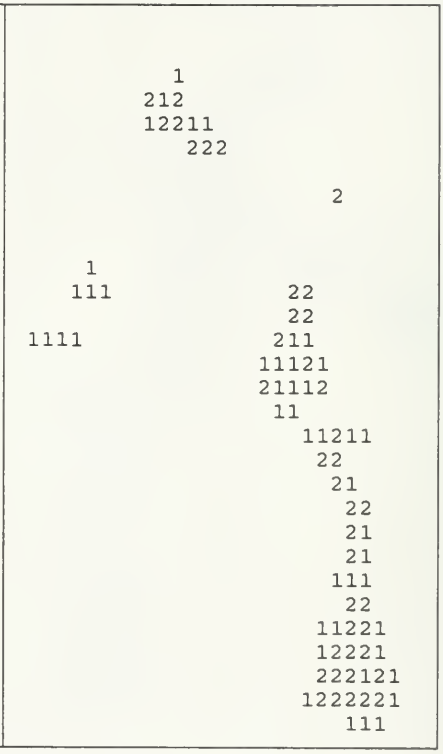


Fig. 5.6e MSS 1986



Map Code	Ratios Legend
1	0.76 - 1.00
2	1.01 - 1.25
3	1.26 - 1.50
4	1.51 - 1.75
5	1.76 - 2.00
6	2.01 - 2.25
7	2.26 - 2.50
8	2.51 - 2.75
9	2.76 - 3.00
#	3.01 - 3.25
@	3.26 - 3.50

5.3 Future Considerations

In this analysis of the temporal characteristics of Bowland Lake, only Bowland has been considered. It would be desirable in the future to include a number of "control" lakes, i.e. lakes which have not been manipulated through liming. These lakes would allow one to simultaneously compare the temporal variations in reflectance for both limed and unlimed lakes.

It is unfortunate that there are no lakes in the immediate vicinity of Bowland which have the requisite data that would allow for these comparisons. However, it is anticipated that data from Lohi Lake (located just south of Sudbury at 46° 23′ 81° 02′) and possibly a number of the Dorset Research Centre study lakes (Girard and Reid 1990) will prove to be suitable for this purpose.

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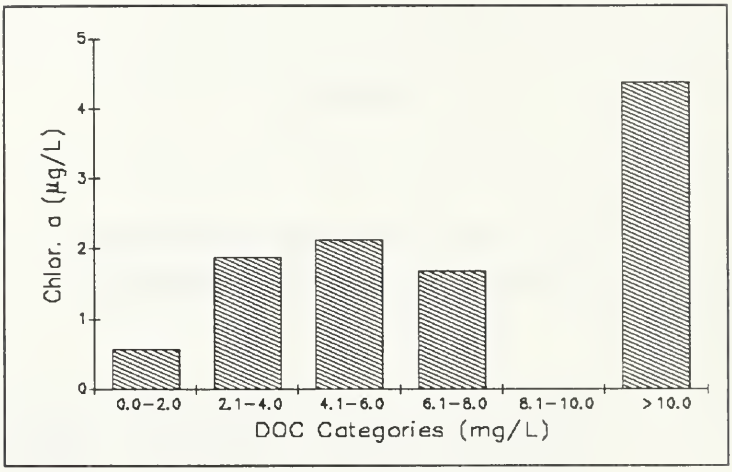
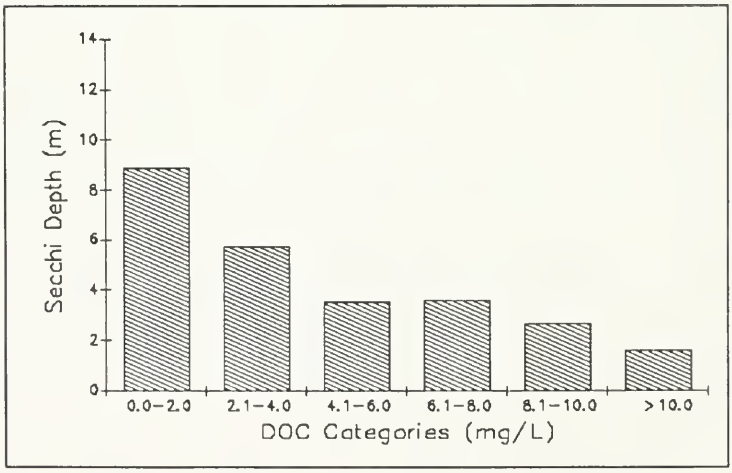
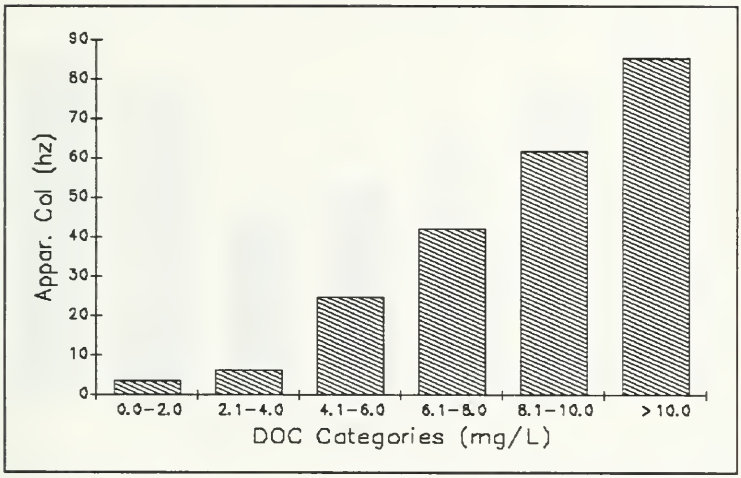
APPENDIX A

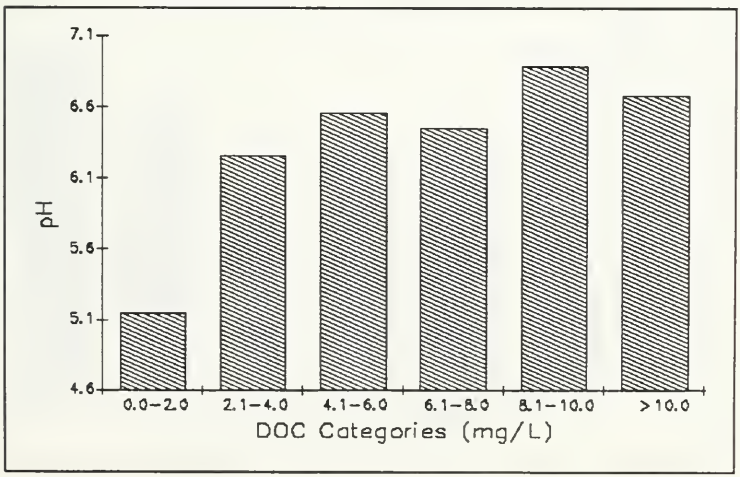
BAR CHARTS OF MEAN LAKE PARAMETERS BY DISSOLVED ORGANIC CARBON CATEGORIES

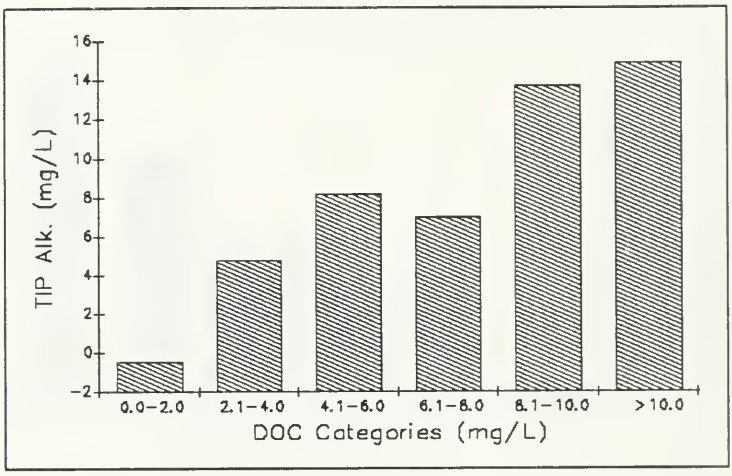
These charts have been prepared using all of the available water chemistry data in the research project's database. (NOTE: n varies from 30 to 521 for the parameters; see Table 3.1, p. 40).

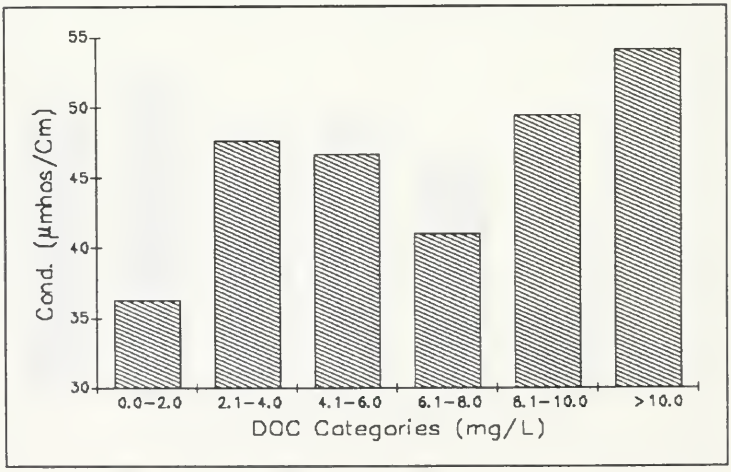

Chlor. a (µg/L)
0
1
2
3
4
5
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
> 10.0
DOC Categories (mg/L)

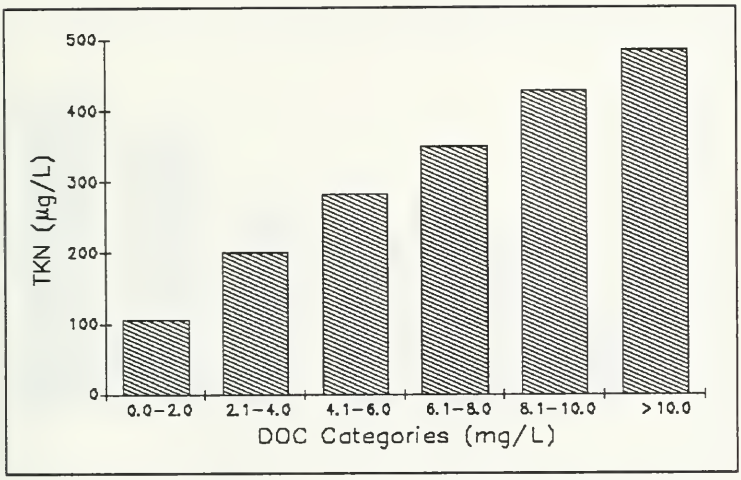

Secchi Depth (m)
0
2
4
6
8
10
12
14
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
> 10.0
DOC Categories (mg/L)

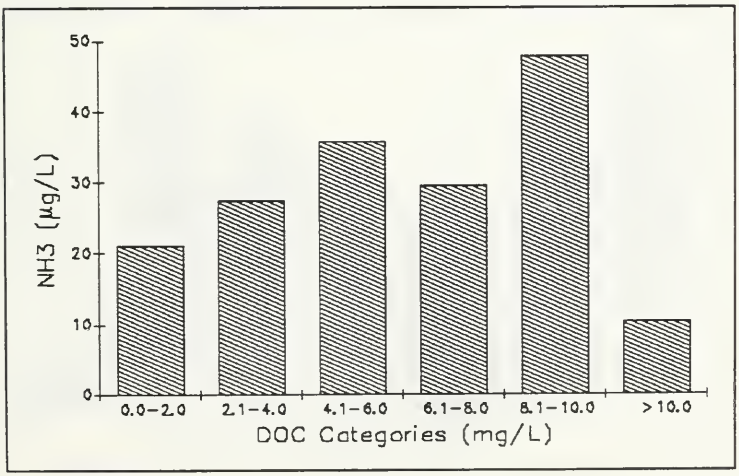

Appar. Col (hz)
90
80
70
60
50
40
30
20
10
0
0.0-2.0
2.1-4.0
4.1-6.0
6.1-8.0
8.1-10.0
>10.0
DOC Categories (mg/L)

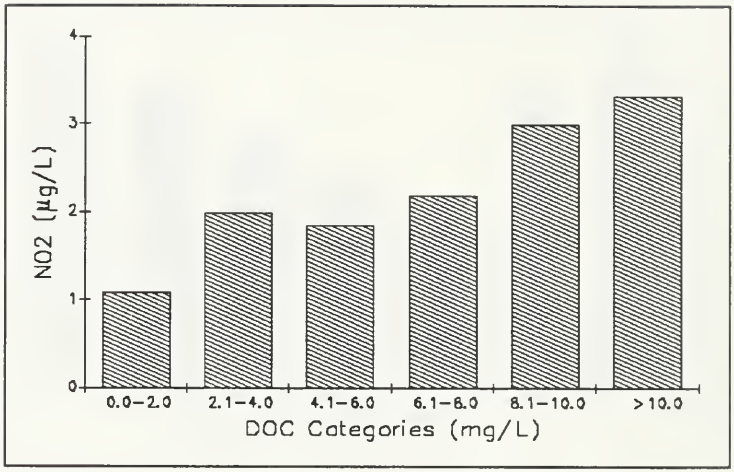

pH
7.1
6.6
6.1
5.6
5.1
4.6
0.0-2.0
2.1-4.0
4.1-6.0
6.1-8.0
8.1-10.0
>10.0
DOC Categories (mg/L)

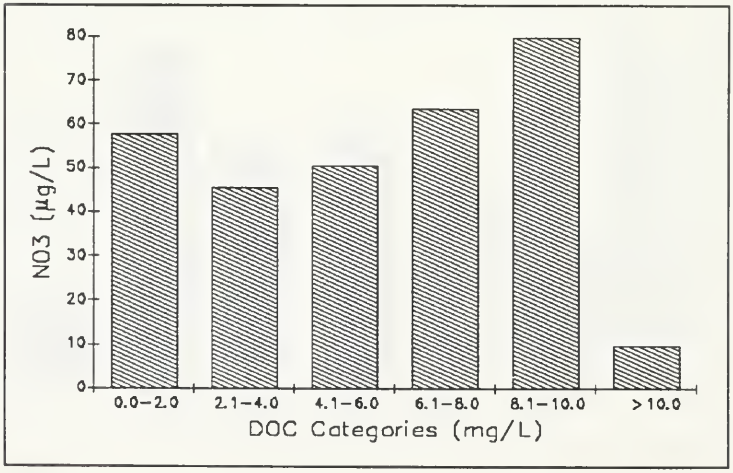

TIP Alk. (mg/L)
16
14
12
10
8
6
4
2
0
-2
0.0-2.0
2.1-4.0
4.1-6.0
6.1-8.0
8.1-10.0
>10.0
DOC Categories (mg/L)

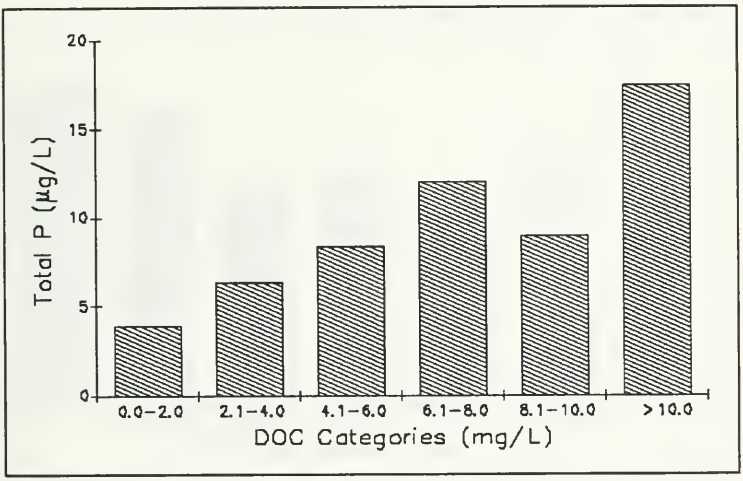

Cond. (µmhos/Cm)
55
50
45
40
35
30
0.0-2.0
2.1-4.0
4.1-6.0
6.1-8.0
8.1-10.0
>10.0
DOC Categories (mg/L)

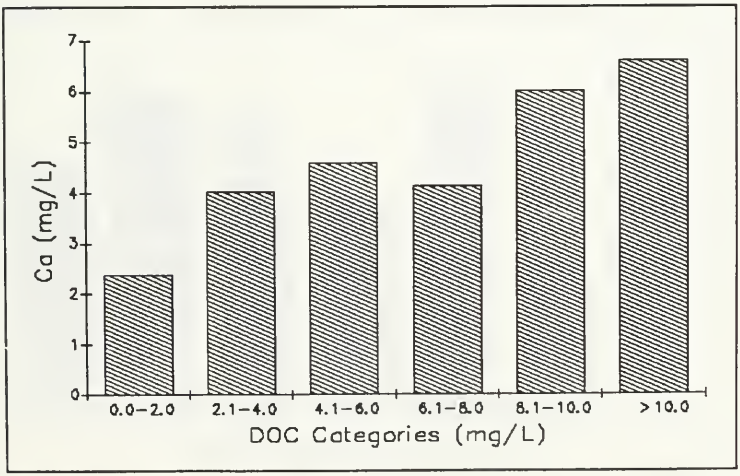

500
400
300
200
100
0
TKN (µg/L)
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
> 10.0
DOC Categories (mg/L)

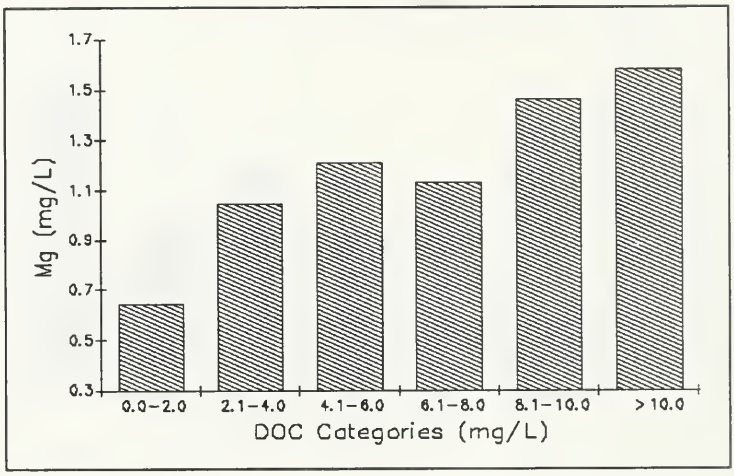

50
40
30
20
10
0
NH3 (µg/L)
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
> 10.0
DOC Categories (mg/L)

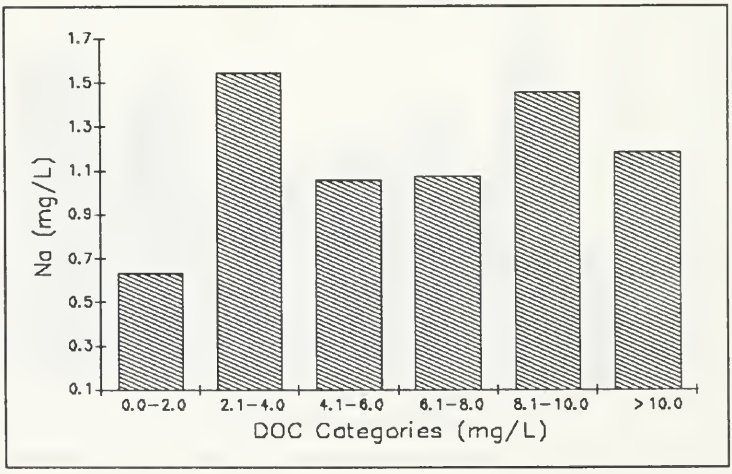

NO2 (µg/L)
0
1
2
3
4
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)

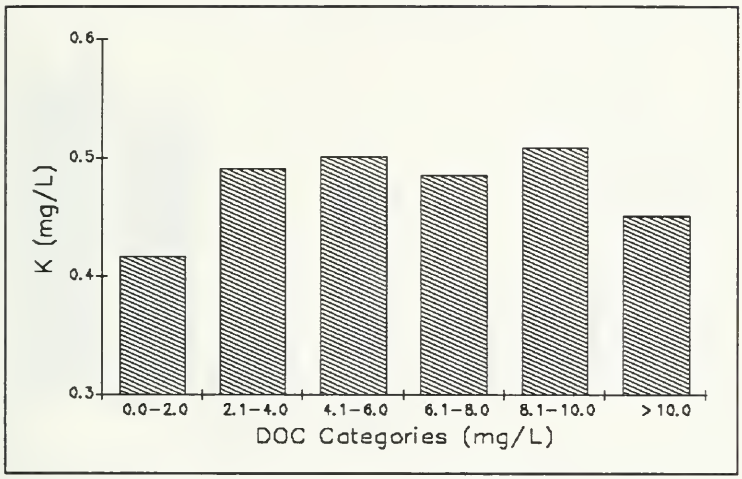

NO3 (µg/L)
0
10
20
30
40
50
60
70
80
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)

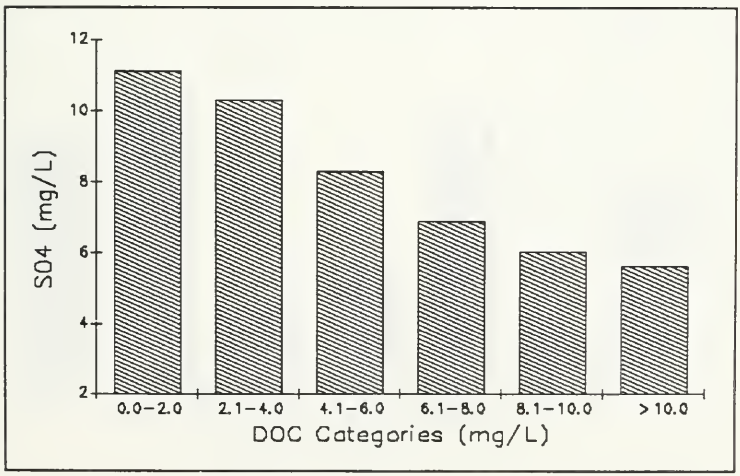

Total P (µg/L)
20
15
10
5
0
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)

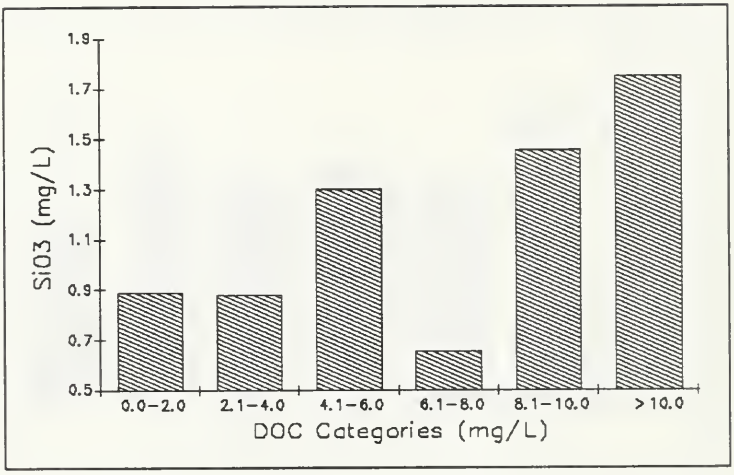

Ca (mg/L)
7
6
5
4
3
2
1
0
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)

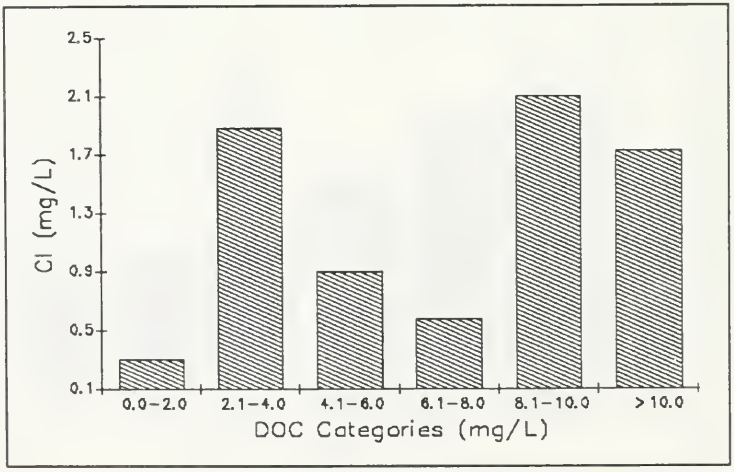

Mg (mg/L)
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.0-2.0
2.1-4.0
4.1-6.0
6.1-8.0
8.1-10.0
> 10.0
DOC Categories (mg/L)

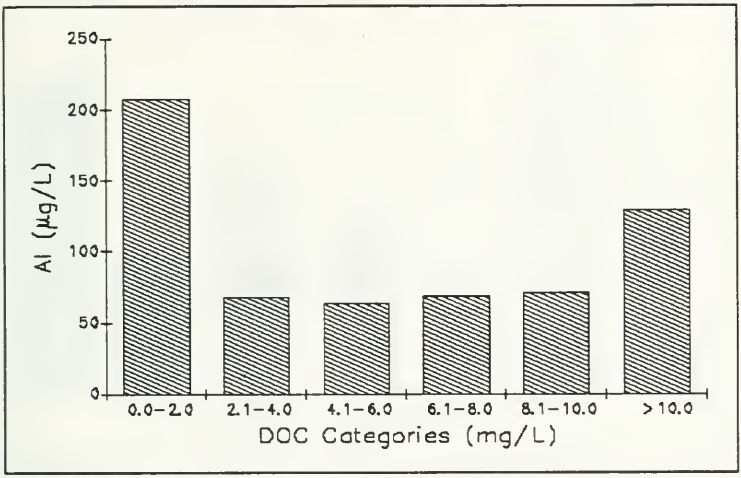

Na (mg/L)
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
0.0-2.0
2.1-4.0
4.1-6.0
6.1-8.0
8.1-10.0
> 10.0
DOC Categories (mg/L)

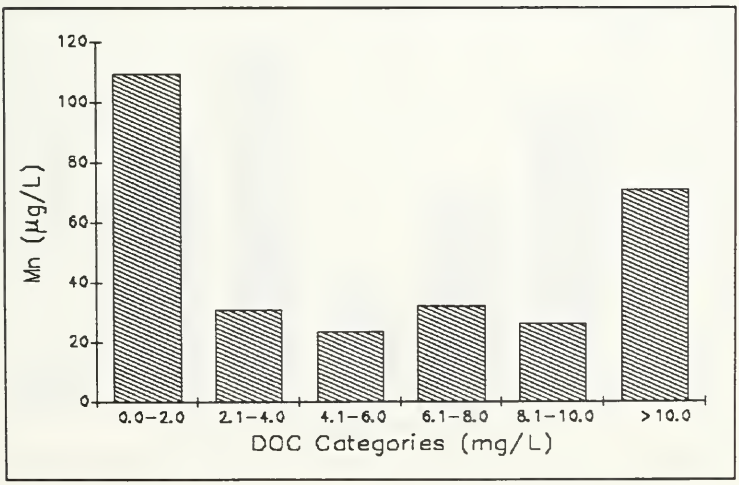

0.6
0.5
0.4
0.3
K (mg/L)
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
> 10.0
DOC Categories (mg/L)

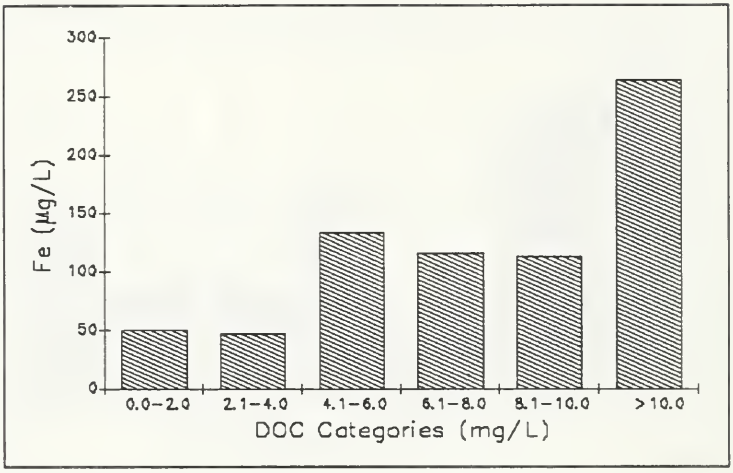

12
10
8
6
4
2
SO4 (mg/L)
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
> 10.0
DOC Categories (mg/L)

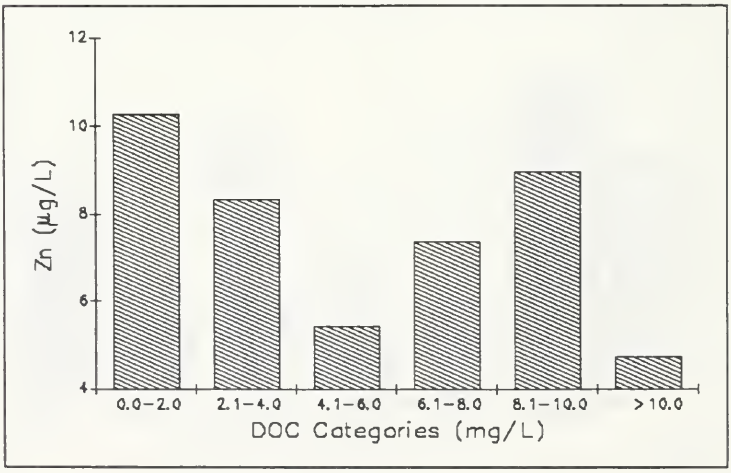

SiO3 (mg/L)
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0.0-2.0
2.1-4.0
4.1-6.0
6.1-8.0
8.1-10.0
> 10.0
DOC Categories (mg/L)

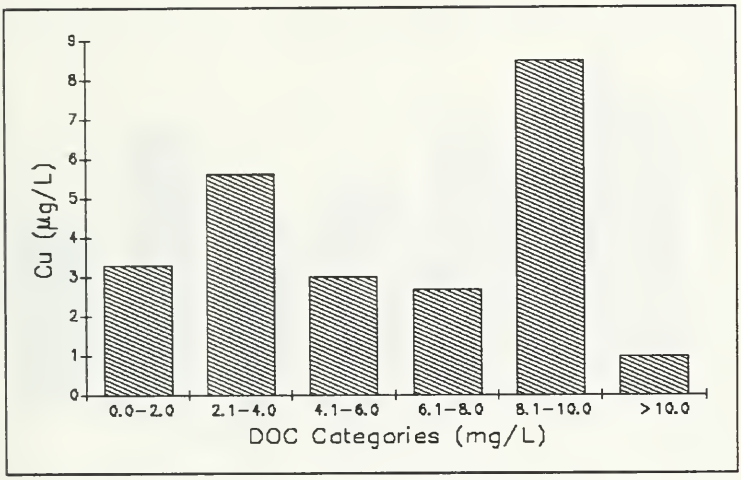

Cl (mg/L)
2.5
2.1
1.7
1.3
0.9
0.5
0.1
0.0-2.0
2.1-4.0
4.1-6.0
6.1-8.0
8.1-10.0
> 10.0
DOC Categories (mg/L)

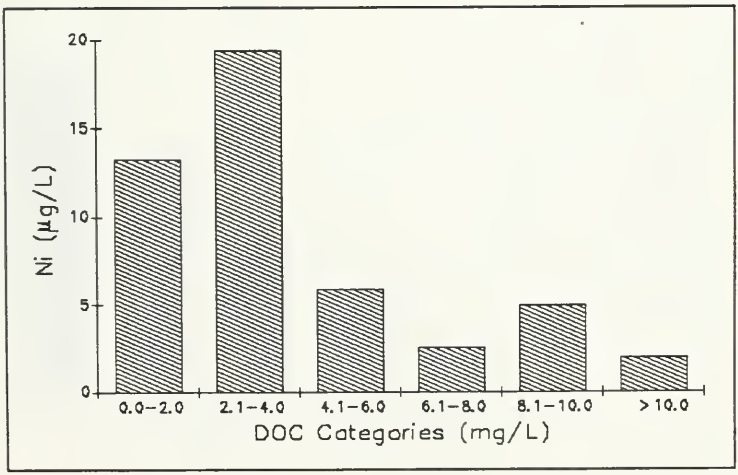

250
200
150
100
50
0
Al (µg/L)
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)

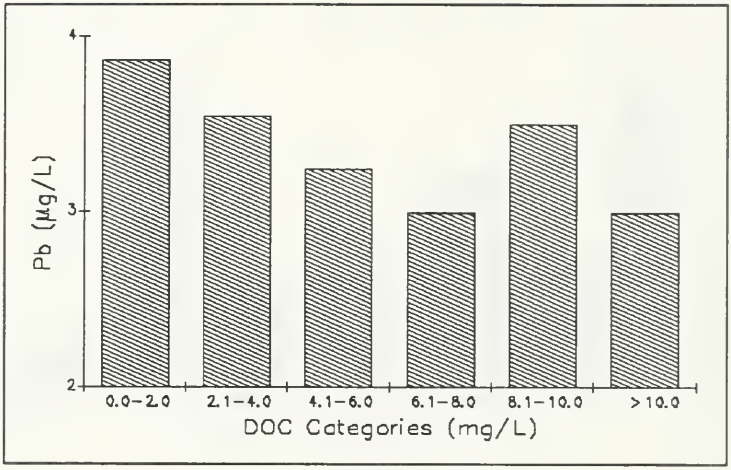

120
100
80
60
40
20
0
Mn (µg/L)
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)

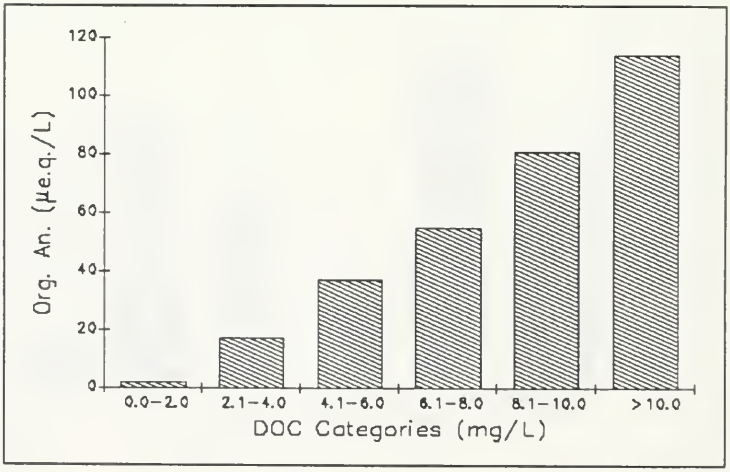

300
250
200
150
100
50
0
Fe (µg/L)
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)

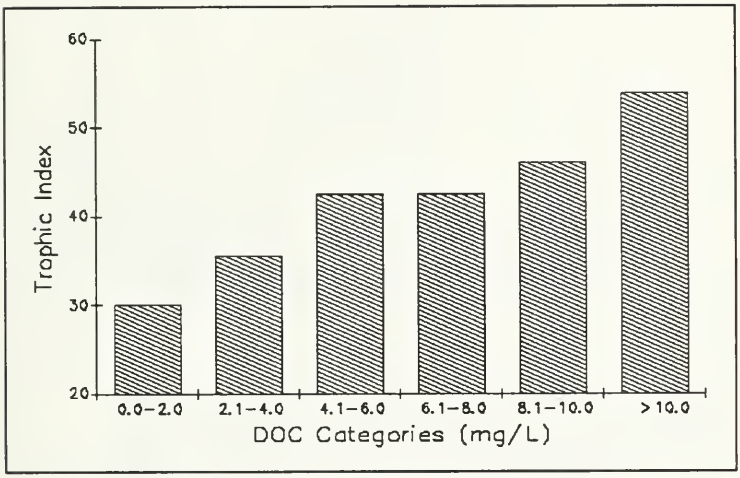

12
10
8
6
4
Zn (µg/L)
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)


Cu (µg/L)
0
1
2
3
4
5
6
7
8
9
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)


Ni (µg/L)
0
5
10
15
20
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)


Pb (µg/L)
4
3
2
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)

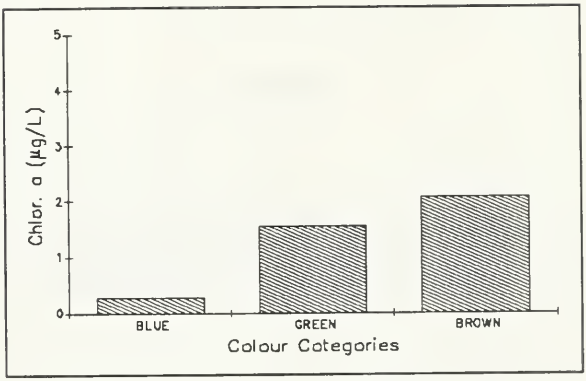

Org. An. (µe.q./L)
120
100
80
60
40
20
0
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
>10.0
DOC Categories (mg/L)

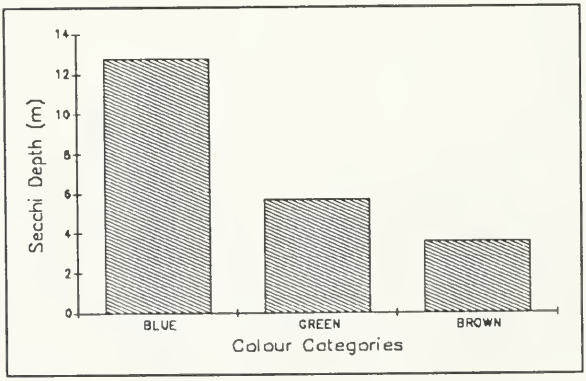

60
50
40
30
20
Trophic Index
0.0–2.0
2.1–4.0
4.1–6.0
6.1–8.0
8.1–10.0
> 10.0
DOC Categories (mg/L)

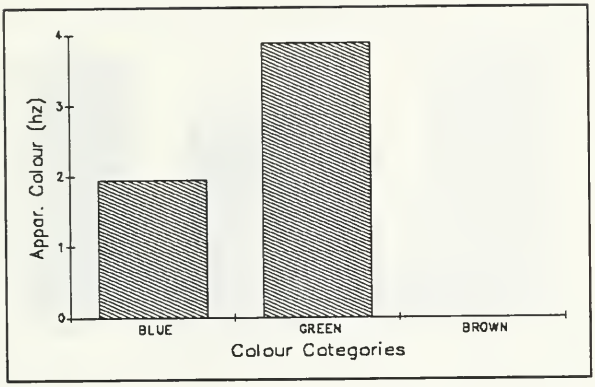
APPENDIX B

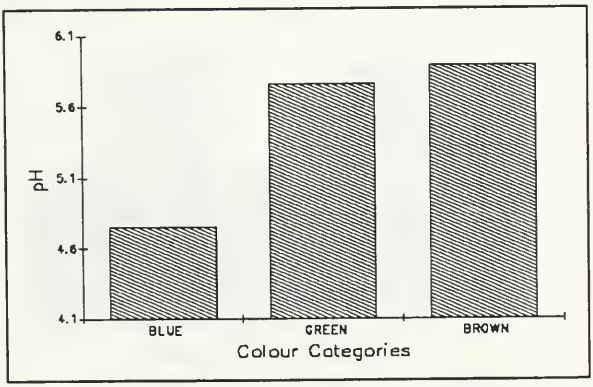
BAR CHARTS OF MEAN LAKE PARAMETERS BY GENERAL WATER COLOUR CATEGORIES

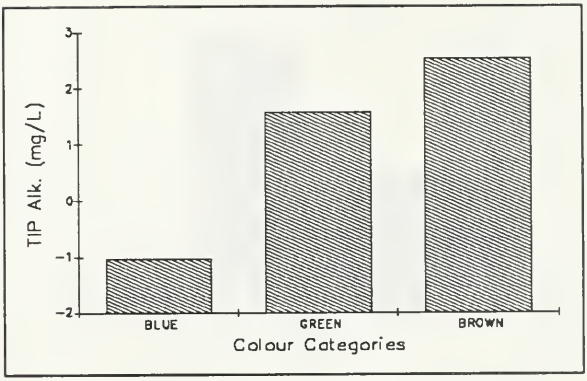
These charts have been prepared for the 118 lakes which had observed visual water colour. These are confined to the Algoma and Sudbury area surveys conducted in August 1986.

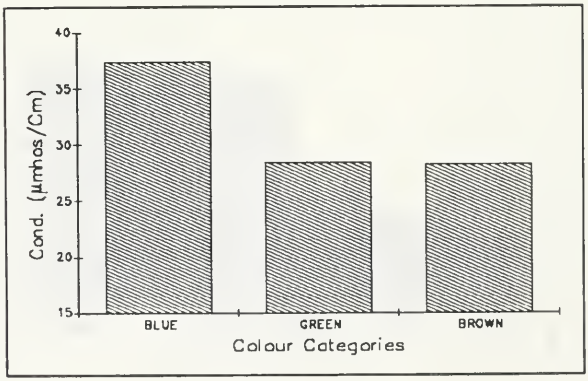

Chlor. a (µg/L)
0
1
2
3
4
5
BLUE
GREEN
BROWN
Colour Categories

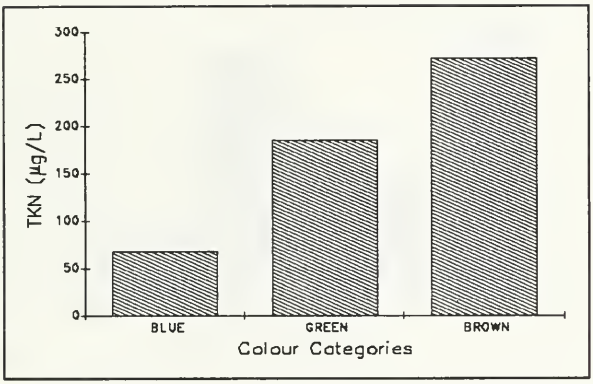

Secchi Depth (m)
0
2
4
6
8
10
12
14
BLUE
GREEN
BROWN
Colour Categories

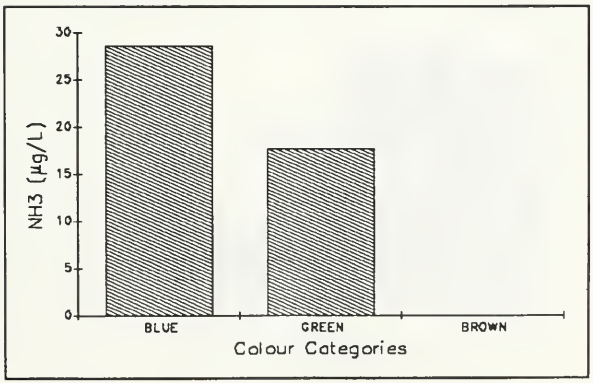

Appar. Colour (hz)
4
3
2
1
0
BLUE
GREEN
BROWN
Colour Categories

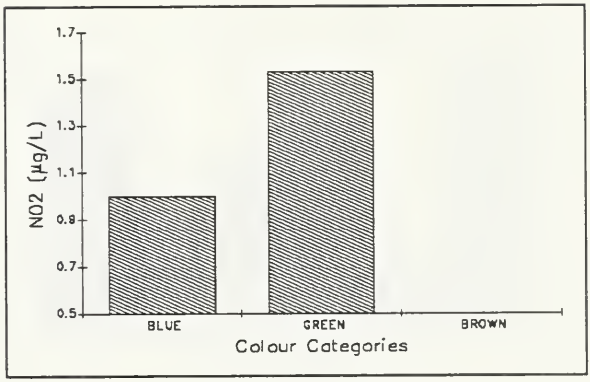

pH
6.1
5.6
5.1
4.6
4.1
BLUE
GREEN
BROWN
Colour Categories

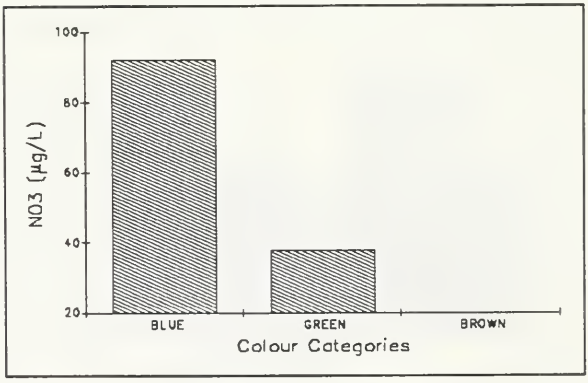

TIP Alk. (mg/L)
3
2
1
0
−1
−2
BLUE
GREEN
BROWN
Colour Categories

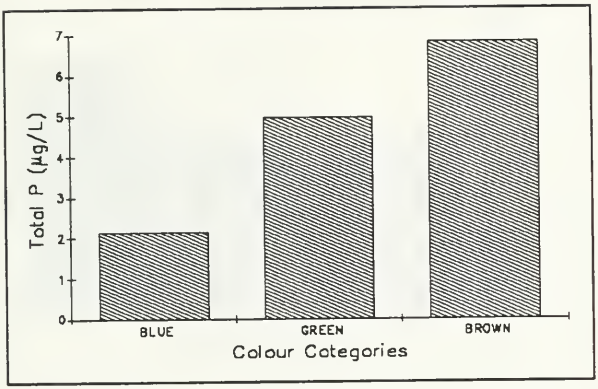

Cond. (µmhos/Cm)
40
35
30
25
20
15
BLUE
GREEN
BROWN
Colour Categories

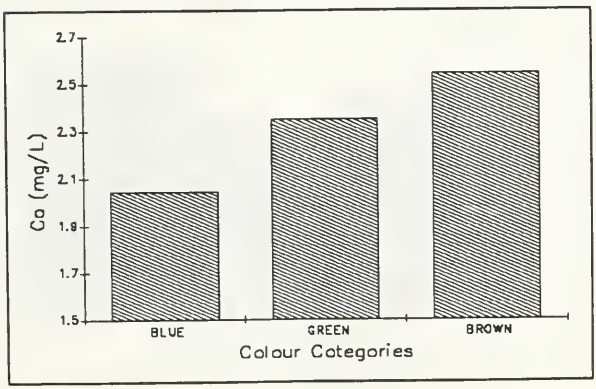

300
250
200
150
100
50
0
TKN (µg/L)
BLUE
GREEN
BROWN
Colour Categories

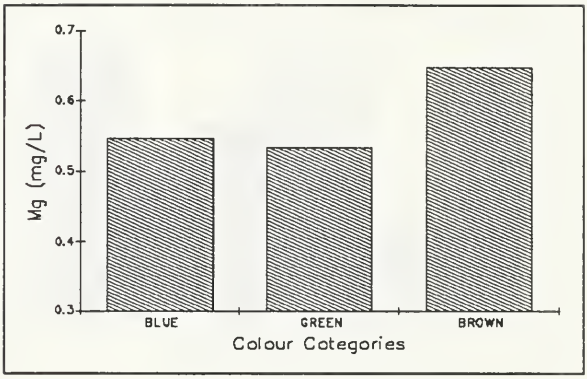

30
25
20
15
10
5
0
NH3 (µg/L)
BLUE
GREEN
BROWN
Colour Categories

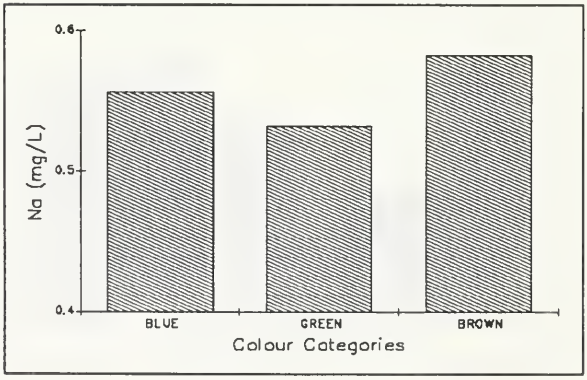

1.7
1.5
1.3
1.1
0.9
0.7
0.5
NO2 (µg/L)
BLUE
GREEN
BROWN
Colour Categories

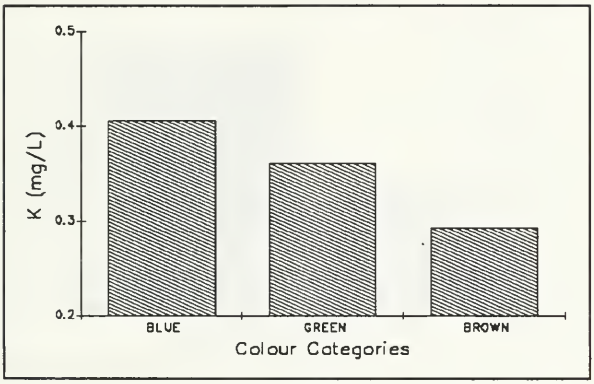

100
80
60
40
20
NO3 (µg/L)
BLUE
GREEN
BROWN
Colour Categories

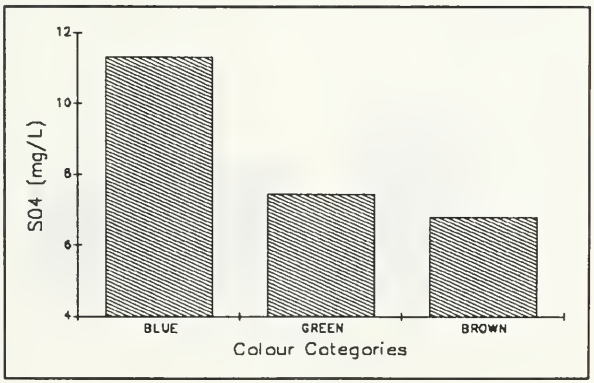

Total P (µg/L)
0
1
2
3
4
5
6
7
BLUE
GREEN
BROWN
Colour Categories

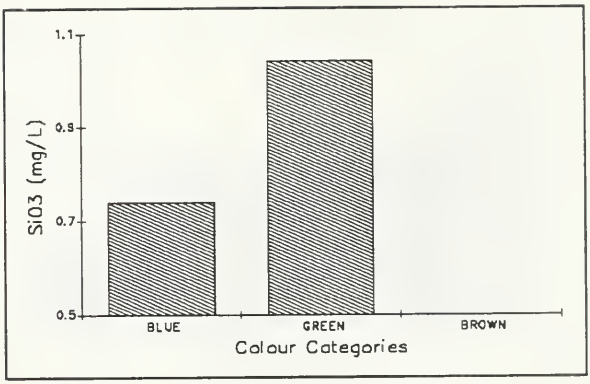

Ca (mg/L)
1.5
1.7
1.8
2.1
2.3
2.5
2.7
BLUE
GREEN
BROWN
Colour Categories

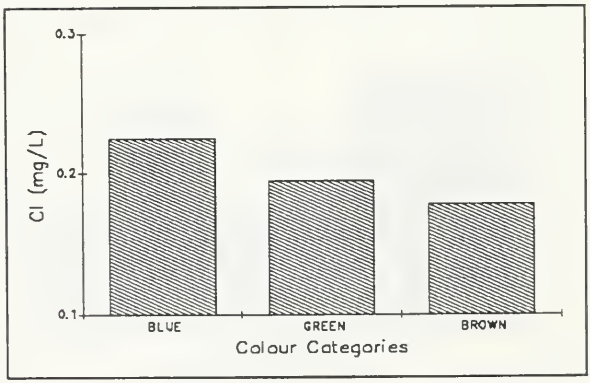

0.7
0.6
0.5
0.4
0.3
Mg (mg/L)
BLUE
GREEN
BROWN
Colour Categories

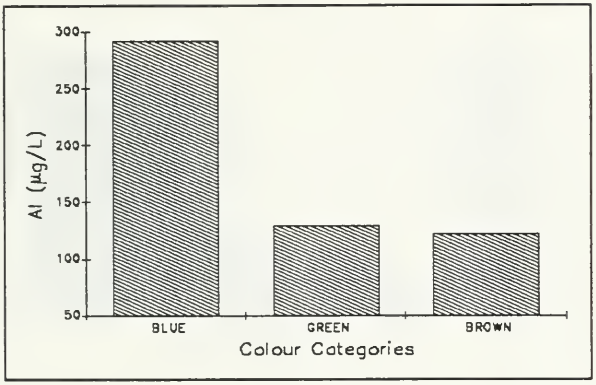

0.6
0.5
0.4
Na (mg/L)
BLUE
GREEN
BROWN
Colour Categories

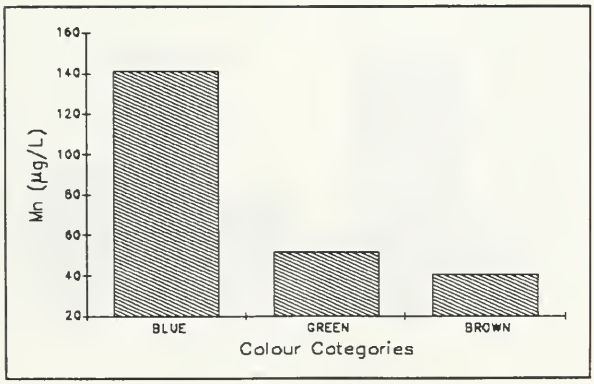

0.5
0.4
0.3
0.2
K (mg/L)
BLUE
GREEN
BROWN
Colour Categories

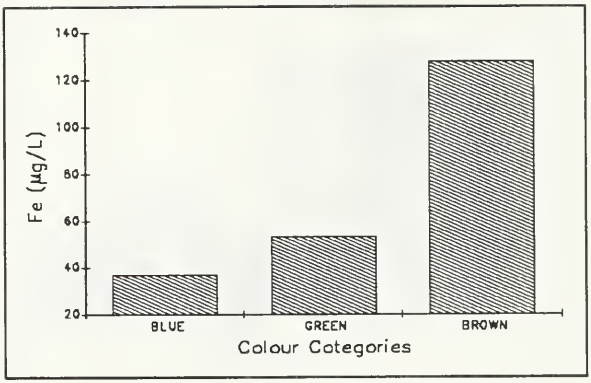

12
10
8
6
4
SO4 (mg/L)
BLUE
GREEN
BROWN
Colour Categories

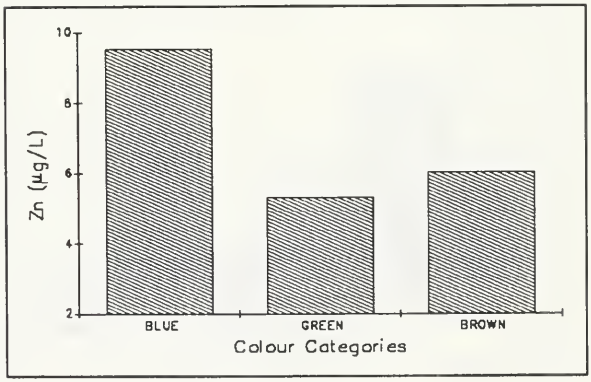

1.1
0.9
0.7
0.5
SiO3 (mg/L)
BLUE
GREEN
BROWN
Colour Categories

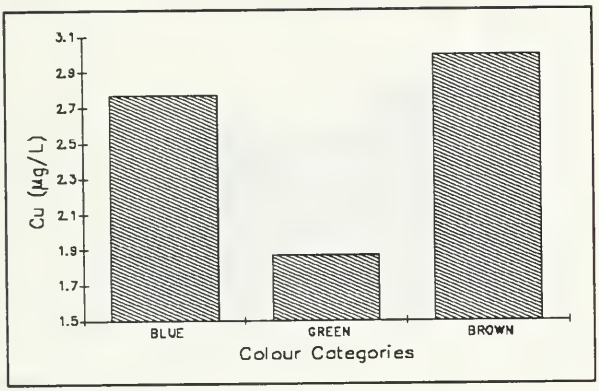

0.3
0.2
0.1
Cl (mg/L)
BLUE
GREEN
BROWN
Colour Categories

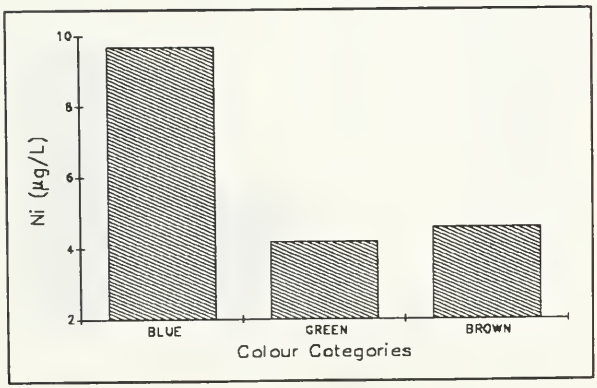

300
250
200
150
100
50
Al (µg/L)
BLUE
GREEN
BROWN
Colour Categories

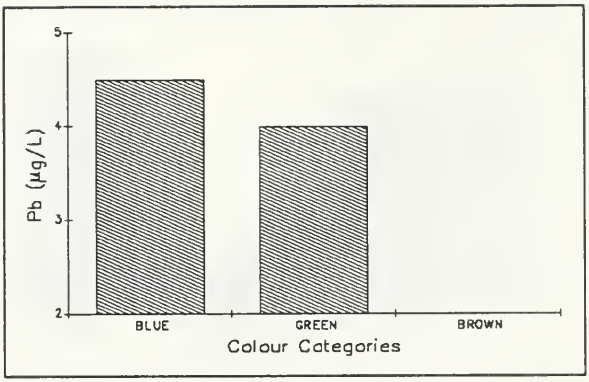

160
140
120
100
80
60
40
20
Mn (µg/L)
BLUE
GREEN
BROWN
Colour Categories

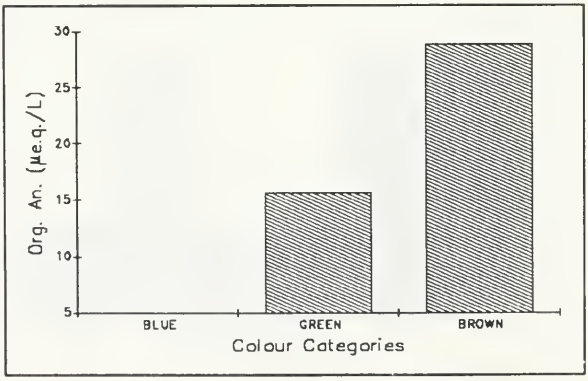

140
120
100
80
60
40
20
Fe (µg/L)
BLUE
GREEN
BROWN
Colour Categories

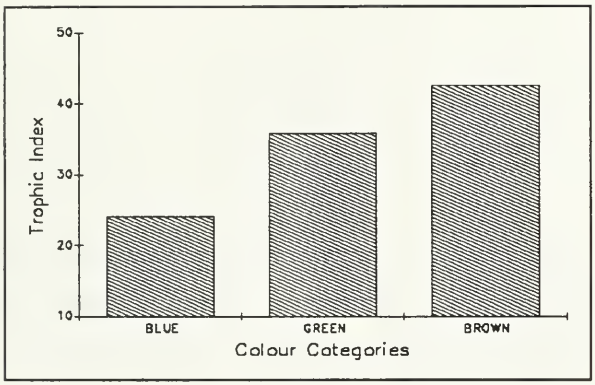

10
8
6
4
2
Zn (µg/L)
BLUE
GREEN
BROWN
Colour Categories


3.1
2.9
2.7
2.5
2.3
2.1
1.9
1.7
1.5
Cu (µg/L)
BLUE
GREEN
BROWN
Colour Categories


10
8
6
4
2
Ni (µg/L)
BLUE
GREEN
BROWN
Colour Categories


5
4
3
2
Pb (µg/L)
BLUE
GREEN
BROWN
Colour Categories


30
25
20
15
10
5
Org. An. (µe.q./L)
BLUE
GREEN
BROWN
Colour Categories


50
40
30
20
10
Trophic Index
BLUE
GREEN
BROWN
Colour Categories

APPENDIX C

CORRELATION COEFFICIENTS COMPARING ASSOCIATIONS BETWEEN DISSOLVED ORGANIC CARBON (OBSERVED AND PREDICTED) WITH ALL AVAILABLE LAKE WATER CHARACTERISTICS

ALL LAKE DATA (n = 30 to 521)

B - correlations of **observed** Log_{10} DOC with lake characteristics in Column A.
C - correlations of **predicted** Log_{10} DOC with lake characteristics in Column A.
D - correlations of **observed** Log_{10} DOC with lake characteristics in Column A **transformed** to Log_{10} (pH ~ hydrogen ion concentrations).
C - correlations of **predicted** Log_{10} DOC with lake characteristics in Column A **transformed** to Log_{10} (pH ~ hydrogen ion concentrations).

** P < 0.01 * P < 0.05

A	B Observed	C Predicted	D Observed	E Predicted
Chlor.	.6542**	.6960**	.8147**	.8206**
Secchi	-.6981**	-.6901**	-.6759**	-.6857**
A. color	.5967**	.5141**	.6225**	.5893**
T. color	.9299	.2838	.9874	.3195
pH	.6009**	.5359**	-.7501**	-.5242**
TIP Alk	.2360**	.3479**	.3097**	.3656**
TFE Alk	.4864**	.4006**	.6723**	.5410**
Conduct	.0599	.1123**	-.0205	.1603**
TKN	.7299**	.6601**	.8546**	.7662**
NH3	-.0651	.1266	-.0710	.1453*
NO2	.1892*	.1736**	.3196**	.2649**
NO3	-.2471**	-.1432*	-.2074*	-.0861
Total P	.4612**	.4570**	.6011**	.5932**
CA	.2140**	.1990**	.3012**	.2529**
MG	.2622**	.2004**	.2848**	.2236**
NA	.2153**	-.0186	.1986**	.1212*
K	.0483	.0414	-.0038	-.0065
SO4	-.4509**	-.3999**	-.4185**	-.4031**
SiO3	.2745**	.2581**	.1667	.2119**
CL	.1541*	.0001	.0529	.0727
AL	-.6015**	-.4718**	-.4186**	-.3291**
MN	-.7256**	-.5914**	-.5405**	-.4290**
FE	.1315	.1809**	.1924**	.2335**
ZN	-.3498**	-.2965**	-.3767**	-.2986**
CU	-.1132	-.1459**	-.1662*	-.1155*
NI	-.2567**	-.1558**	-.5009**	-.3184**
PB	-.3594**	-.2698**	-.3780**	-.2599**
Org.An.	.7201**	.5899**	.9514**	.6457**

LAKE DATA SEPARATED INTO EASTERN AND WESTERN HALVES

n - ranges from 14 to 282 lakes in the eastern half of the study area and from 16 to 279 in western half.
B - correlations of **observed** Log_{10} DOC with lake characteristics in Column A (East).
C - correlations of **predicted** Log_{10} DOC with lake characteristics in Column A (East).
D - correlations of **observed** Log_{10} DOC with lake characteristics in Column A (West).
E - correlations of **predicted** Log_{10} DOC with lake characteristics in Column A (West).

** P < 0.01 * P < 0.05

	East		West	
A	B	C	D	E
	Observed	Predicted	Observed	Predicted
Chlor.	.7348**	.7290**	.5477**	.5254**
Secchi	-.5956**	-.6690**	-.8005**	-.7425**
A. color	.6130**	.4618**	.5805**	.5649**
T. color	.9299	.6343*	.	.5457*
pH	.6936**	.5143**	.4615**	.4149**
TIP Alk	.2579**	.2750**	.3377**	.3338**
TFE Alk	.5618**	.4008**	.3823**	.3296**
Conduct	.1674	.0353	-.1450	.1098
TKN	.7448**	.6440**	.6979**	.6645**
NH3	-.2532*	.1790*	.2045	-.0487
NO2	.2377*	.1729*	.3449*	.1493
NO3	-.0456	.0461	-.5468**	-.5148**
Total P	.5217**	.5245**	.3976**	.3499**
CA	.2770**	.2091**	.1466	.1736*
MG	.3682**	.2382**	.1371	.1901*
NA	.3143**	-.0317	.1078	.0950
K	.2329**	.1538*	-.1278	-.0214
SO4	-.4639**	-.4090**	-.4824**	-.3300**
SiO3	.1685	.1631*	.4005**	.4562**
CL	.2342*	-.0086	.1106	.0634
AL	-.6281**	-.4722**	-.5550**	-.4051**
MN	-.7099**	-.5391**	-.7592**	-.6736**
FE	.1105	.1898**	.2646**	.2105*
ZN	-.3047**	-.1929**	-.3607**	-.4130**
CU	-.0848	-.1313	-.1246	-.0937
NI	-.2165*	-.1478*	-.6781**	-.0846
PB	-.3277**	-.2375**	-.5597**	-.3161**
Org.An.	.7383**	.5517**	.7583**	.6440**

LAKE DATA SEPARATED INTO EASTERN AND WESTERN HALVES

n - ranges from 14 to 282 lakes in the eastern half of the study area and from 16 to 279 in western half.

B - (East) correlations of **observed** Log_{10} DOC with lake characteristics in Column A **transformed** to Log_{10} (pH ~ hydrogen ion concentrations).

C - (East) correlations of **predicted** Log_{10} DOC with lake characteristics in Column A **transformed** to Log_{10} (pH ~ hydrogen ion concentrations).

D - (West) correlations of **observed** Log_{10} DOC with lake characteristics in Column A **transformed** to Log_{10} (pH ~ hydrogen ion concentrations).

E - (West) correlations of **predicted** Log_{10} DOC with lake characteristics in Column A **transformed** to Log_{10} (pH ~ hydrogen ion concentrations).

** P < 0.01 * P < 0.05

	East		West	
A	B	C	D	E
	Observed	Predicted	Observed	Predicted
Chlor.	.8244**	.7998**	.7455**	.7266**
Secchi	-.5928**	-.6616**	-.7562**	-.7201**
A. color	.6032**	.5621**	.6556**	.5960**
T. color	.9874	.6700**	.	.6471**
pH	-.7385**	-.4942**	-.7784**	-.5226**
TIP Alk	.4814**	.2702**	.0435	.2980**
TFE Alk	.7070**	.4923**	.6184**	.5457**
Conduct	.2196*	.0750	-.2010*	.1616**
TKN	.8695**	.7611**	.8379**	.7661**
NH3	-.1644	.1991*	.0558	-.0324
NO2	.3100**	.2628**	.3705*	.2422*
NO3	-.0820	.0282	-.3905**	-.3027**
Total P	.6325**	.6720**	.5693**	.5015**
CA	.5472**	.3176**	.0945	.1713*
MG	.5850**	.3280**	.0673	.1801*
NA	.4296**	.2063**	.0470	.0528
K	.2697**	.1723*	-.1618	-.1017
SO4	-.4187**	-.4114**	-.4593**	-.3761**

(Continued)

A	East		West	
	B Observed	C Predicted	D Observed	E Predicted
SiO3	.0958	.1380	.2628	.3619**
CL	.3433**	.2310**	-.0595	-.0510
AL	-.5075**	-.3844**	-.2951**	-.1853*
MN	-.5705**	-.4212**	-.4952**	-.3535**
FE	.1488	.2557**	.2636**	.2573**
ZN	-.3691**	-.1959**	-.3391**	-.3236**
CU	-.0694	-.0277	-.2208*	-.1863*
NI	-.3886**	-.2494**	-.6580**	-.3405**
PB	-.3402**	-.2170**	-.5548**	-.3080**
Org.An.	.9536**	.6358**	.9500**	.6261**

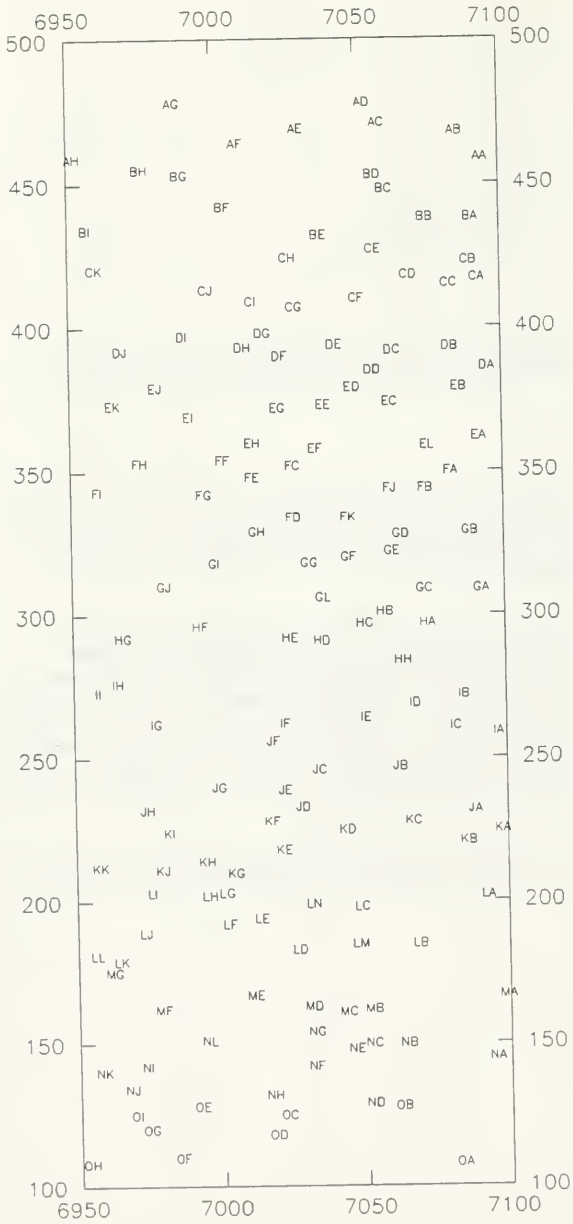
APPENDIX D

SURFACE WATER CHEMISTRY OF THE ALGOMA STUDY LAKES

This appendix lists the lake chemistry data that were acquired in August 1986 specifically for this remote sensing project (see Section 2.2 for sampling and analytical methodologies).

The locations of the lake sampling sites have been identified by both geographic (latitude/longitude) and universal transverse Mercator (UTM) coordinates, the latter to the nearest hundredth meter. The tables list the UTM coordinates in an abbreviated form. For example for Atomic Lake at 7094E 454N, the full UTM reference would be: 16 T **709**400 52**454**00. These lakes can be found on the Michipicoten (41N) National Topographic Survey map (1:250,000).

A map of the lake site locations, using the shortened UTM coordinates, is provided overleaf.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Algoma

ID	Lake Name	Sampling Date	UTM Grid E	UTM Grid N	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min
AA	ATOMIC	20/8/1986	7094	454	47	20	84	14
AB		20/8/1986	7085	463	47	20	84	15
AC		20/8/1986	7058	466	47	21	84	17
AD	EAST	20/8/1986	7053	473	47	21	84	17
AE		20/8/1986	7030	464	47	20	84	19
AF		20/8/1986	7009	459	47	20	84	21
AG	LITTLE AGAWA	20/8/1986	6987	473	47	21	84	22
AH	MADER	20/8/1986	6952	454	47	20	84	25
BA	MALLOT	20/8/1986	7090	433	47	19	84	14
BB		20/8/1986	7074	433	47	19	84	15
BC	MONTREAL RIVER	20/8/1986	7060	443	47	19	84	16
BD		20/8/1986	7056	448	47	20	84	17
BE		20/8/1986	7037	427	47	19	84	18
BF	MONTREAL RIVER	20/8/1986	7004	437	47	19	84	21
BG		20/8/1986	6989	448	47	20	84	22
BH		20/8/1986	6975	450	47	20	84	23
BI		20/8/1986	6957	429	47	19	84	25
CA	DYER	20/8/1986	7092	412	47	18	84	14
CB		20/8/1986	7089	418	47	18	84	14
CC	DYER	20/8/1986	7082	410	47	17	84	15
CD	UNION	20/8/1986	7068	413	47	18	84	16
CE		20/8/1986	7056	422	47	18	84	17
CF		20/8/1986	7050	405	47	17	84	17
CG		20/8/1986	7028	402	47	17	84	19
CH		20/8/1986	7026	419	47	18	84	19
CI		20/8/1986	7014	404	47	17	84	20
CJ		22/8/1986	6998	408	47	18	84	21
CK		22/8/1986	6959	415	47	18	84	25
DA		19/8/1986	7095	381	47	16	84	14
DB		19/8/1986	7082	388	47	16	84	15
DC		19/8/1986	7062	387	47	16	84	17
DD	ALVIN	19/8/1986	7055	380	47	16	84	17
DE		20/8/1986	7042	389	47	16	84	18
DF	BARBARA	20/8/1986	7023	385	47	16	84	20
DG	BARBARA	20/8/1986	7017	393	47	17	84	20
DH	BARBARA	20/8/1986	7010	388	47	16	84	21
DI		20/8/1986	6990	392	47	17	84	22
DJ		20/8/1986	6968	387	47	17	84	24
EA		19/8/1986	7092	357	47	15	84	14
EB		19/8/1986	7085	374	47	16	84	15

ID	Lake Name	Sampling Date	UTM Grid E	UTM Grid N	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min
EC		19/8/1986	7061	369	47	15	84	17
ED	ALVIN	19/8/1986	7048	374	47	16	84	18
EE		22/8/1986	7038	368	47	15	84	18
EF		22/8/1986	7035	353	47	14	84	19
EG		22/8/1986	7022	367	47	15	84	20
EH	HAILEY	22/8/1986	7013	355	47	15	84	20
EI		22/8/1986	6992	364	47	15	84	22
EJ	ROI	22/8/1986	6980	374	47	16	84	23
EK		22/8/1986	6965	368	47	16	84	24
EL		24/8/1986	7074	354	47	15	84	16
FA		19/8/1986	7082	345	47	14	84	15
FB		19/8/1986	7073	339	47	14	84	16
FC	BIG PIKE	22/8/1986	7027	347	47	14	84	19
FD		22/8/1986	7027	329	47	13	84	19
FE	BIG PIKE	22/8/1986	7013	343	47	14	84	21
FF	BIG PIKE	22/8/1986	7003	349	47	14	84	21
FG		22/8/1986	6996	337	47	14	84	22
FH	SHOEPACK	22/8/1986	6974	348	47	14	84	24
FI		22/8/1986	6960	338	47	14	84	25
FJ		24/8/1986	7061	339	47	14	84	17
FK		24/8/1986	7046	329	47	13	84	18
GA		19/8/1986	7092	304	47	12	84	14
GB		19/8/1986	7088	324	47	13	84	14
GC		19/8/1986	7072	304	47	12	84	16
GD		19/8/1986	7064	323	47	13	84	16
GE		19/8/1986	7061	317	47	12	84	17
GF	PATTERSON	22/8/1986	7046	315	47	12	84	18
GG		22/8/1986	7032	313	47	12	84	19
GH		22/8/1986	7014	324	47	13	84	20
GI	RAND	22/8/1986	7000	313	47	12	84	22
GJ		22/8/1986	6982	305	47	12	84	23
GK	BUTTER	22/8/1986	6949	310	47	12	84	26
GL		24/8/1986	7037	301	47	12	84	19
HA		19/8/1986	7073	292	47	11	84	16
HB	CARPENTER	19/8/1986	7058	296	47	11	84	17
HC	CARPENTER	19/8/1986	7051	292	47	11	84	18
HD	MITCHELL	20/8/1986	7036	286	47	11	84	19
HE	MITCHELL	20/8/1986	7025	287	47	11	84	20
HF		22/8/1986	6994	291	47	11	84	22
HG		22/8/1986	6967	287	47	11	84	24

ID	Lake Name	Sampling Date	UTM Grid E	UTM Grid N	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min
HH		24/8/1986	7064	279	47	10	84	17
IA		19/8/1986	7098	254	47	9	84	14
IB		19/8/1986	7086	267	47	10	84	15
IC		19/8/1986	7083	256	47	9	84	15
ID		19/8/1986	7069	264	47	10	84	16
IE		20/8/1986	7052	259	47	9	84	18
IF		20/8/1986	7024	257	47	9	84	20
IG		22/8/1986	6979	257	47	9	84	23
IH	FULLER	22/8/1986	6966	271	47	10	84	24
II	FULLER	22/8/1986	6960	268	47	10	84	25
JA	QUINTET	19/8/1986	7089	227	47	8	84	15
JB	TAY	19/8/1986	7063	242	47	8	84	17
JC		20/8/1986	7035	241	47	8	84	19
JD	NORTH McKINNON	20/8/1986	7029	228	47	8	84	20
JE	NORTH McKINNON	20/8/1986	7023	234	47	8	84	20
JF		22/8/1986	7019	251	47	9	84	20
JG		22/8/1986	7000	235	47	8	84	22
JH		22/8/1986	6975	227	47	8	84	24
KA	QUINTET	19/8/1986	7098	220	47	7	84	14
KB		19/8/1986	7086	216	47	7	84	15
KC		19/8/1986	7067	223	47	8	84	17
KD	McCOLLOUGH	20/8/1986	7044	220	47	7	84	18
KE		20/8/1986	7022	213	47	7	84	20
KF		24/8/1986	7018	223	47	8	84	20
KG	DICK	24/8/1986	7005	205	47	7	84	22
KH		24/8/1986	6995	209	47	7	84	22
KI		22/8/1986	6983	219	47	7	84	23
KJ		24/8/1986	6980	206	47	7	84	23
KK	CHAIN	24/8/1986	6958	207	47	7	84	25
LA		19/8/1986	7093	197	47	6	84	15
LB		19/8/1986	7069	180	47	5	84	16
LC		19/8/1986	7049	193	47	6	84	18
LD		22/8/1986	7027	178	47	5	84	20
LE	McGOVERN	24/8/1986	7014	189	47	6	84	21
LF		24/8/1986	7003	187	47	6	84	22
LG		24/8/1986	7002	198	47	6	84	22
LH		24/8/1986	6996	197	47	6	84	22
LI		24/8/1986	6977	198	47	6	84	24
LJ	GRIFFIN	24/8/1986	6974	184	47	6	84	24
LK	GRIFFIN	24/8/1986	6965	174	47	5	84	25

ID	Lake Name	Sampling Date	UTM Grid E	UTM Grid N	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min
LL	LOWER GRIFFIN	24/8/1986	6957	176	47	5	84	25
LM		24/8/1986	7048	180	47	5	84	18
LN		24/8/1986	7032	194	47	6	84	19
MA		19/8/1986	7099	162	47	4	84	14
MB		22/8/1986	7052	157	47	4	84	18
MC	ADELAIDE	22/8/1986	7043	156	47	4	84	19
MD	ADELAIDE	22/8/1986	7031	158	47	4	84	20
ME		24/8/1986	7011	162	47	4	84	21
MF		24/8/1986	6979	157	47	4	84	24
MG	LOWER GRIFFIN	24/8/1986	6962	170	47	5	84	25
NA		19/8/1986	7095	140	47	3	84	15
NB		19/8/1986	7064	145	47	3	84	17
NC	ADELAIDE	22/8/1986	7052	145	47	3	84	18
ND		22/8/1986	7052	124	47	2	84	18
NE		22/8/1986	7046	143	47	3	84	18
NF	BONE	22/8/1986	7032	137	47	3	84	20
NG		22/8/1986	7032	149	47	4	84	20
NH		24/8/1986	7017	127	47	2	84	21
NI		24/8/1986	6974	137	47	3	84	24
NJ	LITTLE TURKEY	24/8/1986	6968	129	47	3	84	25
NK	TURKEY	24/8/1986	6958	135	47	3	84	25
NL		24/8/1986	6995	146	47	3	84	22
OA		19/8/1986	7083	103	47	1	84	16
OB		22/8/1986	7062	123	47	2	84	17
OC	DREW	24/8/1986	7022	120	47	2	84	20
OD	LITTLE DREW	24/8/1986	7018	113	47	2	84	21
OE		24/8/1986	6992	123	47	2	84	23
OF	TILLEY	24/8/1986	6985	105	47	1	84	23
OG		24/8/1986	6974	115	47	2	84	24
OH		24/8/1986	6953	103	47	1	84	26
OI		24/8/1986	6970	120	47	2	84	25

Lake ID	pH	TFE ALK pH4.5 mg/l	TFE ALK pH3.8 mg/l	TIP ALK mg/l	COND. µmos/cm	Kjeld. N mg/l	TOTAL P mg/l	SUSP. SOLIDS mg/l	DOC (C) mg/l
AA	6.29	3.47	10.55	1.64	20	.24	.007	1	3.3
AB	5.23	1.97	9.46	.15	17	.33	.008	2	6.5
AC	5.35			.29	15	.25	.005	2	4.9
AD	5.20			.10	16	.30	.008	2	5.9
AE	5.03	1.54	8.78	-.33	17	.21	.004	2	3.8
AF	5.60	2.36	9.76	.50	17	.30	.006	1	4.5
AG	6.01	2.78	10.04	.96	17	.23	.004	1	4.2
AH	5.43	1.79	8.95	-.05	15	.13	.002	1	1.4
BA	5.59	2.53	10.02	.67	18	.31	.008	1	6.0
BB	5.59	2.22	9.50	.37	16	.24	.006	1	3.1
BC	7.19	16.66	24.71	14.86	44	.37	.009	1	7.6
BD	5.04	1.56	8.83	-.33	17	.27	.006	1	3.6
BE	4.78	1.16	9.03	-.75	22	.41	.016	4	8.7
BF	7.19	16.01	24.23	14.19	43	.32	.007	1	7.5
BG	5.29	2.00	9.41	.11	16	.24	.005	1	3.4
BH	5.28	1.75	9.11	-.31	16	.16	.004	1	1.7
BI	4.77	1.01	8.56	-.87	17	.30	.008	2	3.6
CA	5.20			.09	18	.30	.006	1	6.1
CB	5.82	2.77	10.27	.86	19	.25	.005	1	4.8
CC	5.31	2.11	9.70	.18	17	.30	.006	1	5.9
CD	5.38			.32	17	.26	.007	1	5.6
CE	5.14	1.75	9.14	-.19	16	.32	.006	1	4.1
CF	5.77	2.46	9.96	.57	17	.27	.006	1	3.8
CG	4.92	1.53	9.28	-.44	17	.54	.021	3	5.6
CH	5.41	2.19	9.76	.27	16	.29	.006	1	3.9
CI	4.85	1.41	9.40	-.60	17	.41	.013	3	8.5
CJ	5.06	1.58	9.15	-.35	15	.29	.019	1	3.2
CK	4.71			-.94	16	.34	.010	1	3.9
DA	5.16	1.98	9.64	.07	18	.34	.007	1	6.1
DB	4.54	.24	8.59	-1.55	23	.72	.014	1	19.0
DC	5.20	1.99	9.62	.10	18	.35	.007	2	5.5
DD	5.66	2.27	9.80	.36	16	.25	.005	2	3.9
DE	5.32	1.90	9.24	-.06	16	.26	.004	1	3.5
DF	5.36	1.73	8.62	-.07	16	.15	.001	1	1.8
DG	5.24	1.69	8.74	-.11	16	.17	.005	1	3.3
DH	5.37	1.78	8.74	-.01	16	.14	.002	1	2.5
DI	5.24	1.78	8.93	-.06	15	.23	.005	1	3.9
DJ	5.12	1.64	8.78	-.19	15	.22	.005	1	4.1
EA	4.98	1.53	9.10	-.41	18	.25	.006	1	4.2
EB	5.19	1.97	9.59	.06	17	.41	.009	2	5.2

Lake ID	pH	TFE ALK pH4.5 mg/l	TFE ALK pH3.8 mg/l	TIP ALK mg/l	COND. µmos/cm	Kjeld. N mg/l	TOTAL P mg/l	SUSP. SOLIDS mg/l	DOC (C) mg/l
EC	5.74	2.71	9.75	1.04	18	.33	.006	1	5.3
ED	5.65	2.28	9.83	.37	16	.28	.005	1	3.4
EE	5.47	1.95	8.92	.10	12	.22	.005	1	2.9
EF	5.23	1.96	9.49	.10	17	.33	.009	2	6.2
EG	5.17			-.13	16	.28	.006	1	4.6
EH	5.32			-.02	15	.21	.003	1	3.6
EI	5.24	1.70	8.52	-.05	17	.24	.004	1	3.5
EJ	4.85	1.22	8.55	-.59	17	.30	.007	1	5.6
EK	6.48	5.05	12.19	3.27	19	.35	.009	2	4.6
EL	5.31	1.99	8.82	.22	18	.32	.011	1	5.2
FA	5.25	1.68	9.00	-.21	17	.16	.002	1	1.3
FB	4.82	1.14	8.30	-.64	19	.25	.004	1	4.4
FC	5.54	2.30	9.66	.49	16	.29	.007	1	4.7
FD	4.70	.89	8.44	-.97	16	.69	.022	4	9.2
FE	5.57	2.13	9.07	.33	16	.25	.003	2	4.0
FF	5.64	2.08	8.91	.30	16	.24	.004	1	4.0
FG	6.31	3.73	10.69	1.98	19	.33	.006	1	3.9
FH	7.16	11.43	18.78	9.63	33	.28	.005	1	5.1
FI	4.98	1.34	8.33	-.46	16	.29	.008	1	3.1
FJ	4.73	.92	8.21	-.88	17	.46	.018	3	7.0
FK	5.33	1.90	8.64	.17	15	.31	.009	1	4.5
GA	6.54	4.11	11.49	2.19	19	.18	.002	1	2.2
GB	5.12	1.80	9.37	-.17	17	.27	.005	1	4.3
GC	5.39	1.98	9.05	.26	16	.22	.007	1	3.3
GD	5.36	2.01	9.14	.26	18	.26	.006	1	3.7
GE	5.11	1.59	8.56	-.23	19	.66	.012	1	3.6
GF	5.81	2.28	9.46	.47	16	.23	.005	1	2.9
GG	5.57			.45	17	.32	.005	2	5.5
GH	5.19	1.78	8.85	-.06	16	.39	.011	2	5.4
GI	6.22	3.01	9.97	1.21	18	.20	.003	2	3.2
GJ	5.85	2.45	9.49	.63	16	.23	.007	2	3.4
GK	6.18	3.21	10.29	1.39	19	.25	.008	2	3.3
GL	5.75	3.11	10.22	1.43	18	.48	.012	2	8.1
HA	6.46	4.42	11.84	2.57	21	.38	.007	1	4.9
HB	6.27	3.10	10.25	1.33	18	.18	.006	1	3.0
HC	6.37	3.13	10.38	1.32	18	.18	.007	1	2.9
HD	7.07	8.91	16.39	7.09	28	.28	.006	2	5.5
HE	6.71	8.70	16.19	6.83	29	.42	.013	3	5.2
HF	5.47	2.10	9.11	.30	16	.35	.008	1	4.3
HG	5.68	2.96	10.22	1.09	15	.42	.015	2	5.8

Lake ID	pH	TFE ALK pH4.5 mg/l	TFE ALK pH3.8 mg/l	TIP ALK mg/l	COND. µmos/cm	Kjeld. N mg/l	TOTAL P mg/l	SUSP. SOLIDS mg/l	DOC (C) mg/l
HH	6.07	4.60	11.67	2.88	20	.53	.017	2	8.1
IA	5.94	4.21	11.84	2.31	19	.33	.009	1	5.1
IB	5.92	3.90	11.66	2.03	18	.42	.011	2	7.2
IC	5.70	3.79	11.55	1.87	18	.43	.014	3	4.5
ID	5.58	3.26	10.94	1.57	20	.65	.170	1	13.4
IE	5.44	3.14	10.97	1.28	20	.50	.013	1	12.6
IF	6.83	9.84	17.24	7.98	31	.36	.008	1	5.0
IG	6.25	3.59	10.64	1.79	19	.25	.005	1	3.9
IH	6.70	6.54	13.72	4.71	24	.31	.009	2	4.6
II	6.66	6.51	13.76	4.67	24	.33	.009	3	4.5
JA	6.83	5.08	12.69	3.14	23	.21	.003	1	3.0
JB	5.83	3.87	11.43	2.17	19	.47	.014	2	10.5
JC	5.98	3.97	11.31	2.17	17	.56	.022	2	5.9
JD	6.34	6.54	14.01	4.71	23	.32	.006	1	6.9
JE	7.10	9.28	16.79	7.45	29	.28	.005	1	9.1
JF	6.41	6.14	13.50	4.27	23	.53	.015	1	6.4
JG	5.73	2.72	10.14	.87	18	.34	.008	1	6.6
JH	6.92	9.92	17.41	8.10	29	.29	.008	1	5.1
KA	6.79	5.09	12.48	3.16	23	.19	.003	1	3.1
KB	6.69	6.10	13.65	4.17	25	.24	.006	1	3.3
KC	6.69	7.61	15.20	5.84	26	.47	.011	2	7.6
KD	6.27	6.18	13.95	4.33	22	.35	.008	2	4.9
KE	6.84	13.24	20.95	11.35	35	.34	.009	1	5.9
KF	7.02	10.46	17.38	8.68	31	.43	.012	2	4.8
KG	7.20	11.15	18.26	9.42	33	.26	.007	2	4.5
KH	6.34	4.48	11.72	2.66	21	.34	.007	1	6.3
KI	5.70	3.23	10.73	1.33	19	.39	.012	1	8.0
KJ	6.36	3.87	10.75	2.09	20	.31	.010	1	3.4
KK	6.63	5.02	12.03	3.17	23	.25	.011	1	3.5
LA	7.20	11.32	19.11	9.42	32	.44	.008	1	3.8
LB	6.90	16.66	24.85	14.95	41	.45	.010	2	9.2
LC	6.89	10.87	18.50	9.09	33	.41	.007	2	7.1
LD	6.91	11.62	19.11	9.78	32	.46	.011	2	5.8
LE	7.43	16.37	23.44	14.56	41	.21	.003	1	3.0
LF	6.50	6.62	13.62	4.83	25	.24	.004	1	3.5
LG	7.14	9.88	17.03	8.08	31	.25	.004	1	4.1
LH	7.13	9.75	16.74	8.03	31	.25	.012	1	4.1
LI	5.87	2.59	9.45	.84	17	.28	.006	1	4.3
LJ	7.03	7.62	14.51	5.83	30	.16	.001	1	3.6
LK	7.06	7.63	14.58	5.82	30	.17	.004	1	2.8

Lake ID	pH	TFE ALK pH4.5 mg/l	TFE ALK pH3.8 mg/l	TIP ALK mg/l	COND. µmos/cm	Kjeld. N mg/l	TOTAL P mg/l	SUSP. SOLIDS mg/l	DOC (C) mg/l
LL	6.99	7.46	14.58	5.65	29	.18	.004	1	2.9
LM	6.39	10.30	18.52	8.46	31	.49	.007	1	13.0
LN	6.65	12.92	20.53	11.03	39	.53	.012	2	6.8
MA	5.51	2.88	10.91	.95	16	.52	.012	2	8.1
MB	7.21	9.61	16.81	7.74	31	.23	.005	1	2.6
MC	7.24	9.22	16.55	7.36	31	.25	.006	1	2.5
MD	7.19	9.66	17.17	7.73	32	.24	.005	1	2.5
ME	6.93	9.32	16.69	7.45	31	.29	.004	1	3.8
MF	6.47	4.61	11.84	2.77	22	.30	.003	2	4.2
MG	7.05	7.54	14.71	5.66	29	.18	.001	1	2.9
NA	6.55	4.87	12.37	2.96	24	.28	.005	1	3.2
NB	6.89	6.44	13.68	4.62	24	.29	.006	1	3.0
NC	7.20	9.22	16.69	7.30	31	.22	.004	2	2.6
ND	6.19	3.28	10.63	1.39	20	.23	.005	1	3.0
NE	6.46	4.38	11.82	2.48	21	.26	.005	1	4.0
NF	6.49	4.81	12.38	2.84	21	.22	.005	1	3.1
NG	6.60	4.30	11.79	2.37	21	.18	.003	1	2.1
NH	6.87	16.28	23.89	14.38	43	.52	.017	4	5.1
NI	6.95	8.08	15.19	6.19	28	.33	.007	3	3.9
NJ	7.28	9.93	17.12	8.10	33	.25	.005	1	3.0
NK	7.38	11.39	18.41	9.55	37	.22	.005	1	2.9
NL	6.18	4.51	11.74	2.69	22	.30	.008	1	4.9
OA	5.83	2.95	10.49	1.04	18	.38	.025	1	3.7
OB	5.84	3.06	10.71	1.11	18	.33	.007	1	5.7
OC	7.02	9.84	16.73	8.14	33	.24	.005	1	3.7
OD	7.03	10.87	17.97	9.11	33	.36	.007	2	4.4
OE	7.06	14.07	21.19	12.31	41	.47	.012	3	4.5
OF	7.35	13.92	21.16	12.14	40	.27	.007	3	3.5
OG	7.04	14.86	22.33	13.16	40	.40	.009	1	7.4
OH	6.61	12.26	19.66	10.61	33	.50	.011	1	9.7
OI	6.82	16.87	24.50	15.07	44	.41	.007	1	8.4

Lake ID	SO4 mg/l	Cl mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cu µg/l	Ni µg/l
AA	4.58	.20	1.60	.43	.42	.38	1	2
AB	3.86	.05	1.30	.37	.35	.10	1	2
AC	3.45	.07	1.10	.28	.27	.10	1	2
AD	3.20	.08	1.00	.27	.26	.10	1	2
AE	3.92	.05	.77	.27	.26	.16	1	2
AF	4.05	.07	1.00	.35	.33	.20	1	2
AG	3.76	.08	1.20	.34	.33	.22	1	2
AH	4.08	.10	.83	.25	.31	.19	1	2
BA	4.05	.07	1.40	.31	.42	.16	1	2
BB	4.08	.15	1.20	.26	.38	.15	1	2
BC	4.46	.24	6.20	1.40	.60	.46	1	2
BD	4.17	.07	.99	.32	.30	.20	1	2
BE	3.01	1.20	.93	.25	.31	1.20	6	2
BF	4.39	.12	5.80	1.30	.61	.40	5	2
BG	3.86	.06	.75	.33	.30	.27	1	2
BH	4.01	.08	.72	.26	.28	.22	1	2
BI	3.17	.07	.51	.13	.20	.16	1	2
CA	3.70	.14	1.30	.31	.34	.20	1	2
CB	4.33	.17	1.60	.34	.45	.27	8	2
CC	3.83	.07	1.20	.31	.36	.15	6	2
CD	3.83	.07	1.30	.31	.35	.20	6	2
CE	3.45	.06	.88	.21	.35	.15	3	2
CF	4.08	.15	1.20	.32	.40	.24	6	2
CG	3.32	.08	.83	.22	.30	.15	5	2
CH	3.57	.12	.99	.27	.35	.20	5	2
CI	3.10	.10	.93	.23	.36	.19	4	2
CJ	3.55	.09	.77	.23	.25	.32	1	2
CK	3.16	.31	.67	.19	.20	.48	1	2
DA	3.67	.09	1.40	.28	.33	.17	1	2
DB	2.29	.01	1.60	.25	.28	.04	1	2
DC	4.00	.11	1.40	.29	.40	.16	1	2
DD	3.83	.14	1.40	.27	.35	.17	1	2
DE	3.89	.14	.88	.29	.36	.21	1	2
DF	4.30	.12	.96	.26	.33	.17	1	2
DG	3.89	.11	1.00	.25	.30	.13	1	2
DH	4.23	.14	1.00	.26	.33	.17	1	2
DI	3.57	.08	.83	.24	.33	.16	1	2
DJ	3.42	.02	.75	.21	.32	.10	1	2
EA	3.89	.18	.94	.21	.29	.10	1	2
EB	3.69	.11	1.20	.24	.39	.09	1	2

Lake ID	SO4 mg/l	Cl mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cu µg/l	Ni µg/l
EC	3.47	.21	1.60	.22	.34	.36	1	3
ED	3.78	.11	1.20	.29	.34	.16	1	2
EE	2.99	.05	.77	.22	.27	.16	1	2
EF	3.93	.06	1.20	.33	.44	.10	1	2
EG	3.82	.01	.91	.32	.35	.12	1	3
EH	4.04	.07	.99	.24	.33	.15	1	2
EI	4.16	.24	.91	.32	.35	.35	1	2
EJ	3.77	.01	.85	.27	.27	.07	1	2
EK	3.96	.03	1.80	.50	.44	.14	1	2
EL	3.51	.29	1.30	.29	.33	.31	1	2
FA	4.73	.14	1.10	.28	.34	.14	1	2
FB	3.72	.04	.92	.19	.27	.09	1	2
FC	4.04	.05	1.20	.34	.36	.14	1	2
FD	2.32	.01	.59	.27	.20	.04	1	2
FE	4.04	.01	1.00	.32	.36	.16	1	2
FF	4.10	.01	1.10	.32	.34	.16	1	2
FG	4.52	.03	1.70	.49	.48	.13	2	2
FH	4.38	.01	4.20	.87	.62	.34	1	2
FI	4.18	.01	.91	.28	.27	.10	1	2
FJ	3.24	.11	.85	.26	.26	.07	1	2
FK	3.31	.01	.88	.31	.29	.04	1	2
GA	4.68	.10	2.00	.40	.40	.14	1	2
GB	3.86	.06	1.10	.28	.39	.09	1	2
GC	3.95	.05	1.20	.26	.40	.14	1	2
GD	4.56	.09	1.30	.36	.36	.14	1	3
GE	4.73	.09	.84	.28	.25	.17	1	2
GF	4.27	.05	1.10	.38	.38	.20	1	2
GG	4.04	.04	1.10	.36	.43	.14	1	2
GH	3.55	.01	1.00	.28	.30	.16	1	2
GI	4.13	.35	1.30	.36	.39	.65	1	2
GJ	4.21	.07	1.20	.32	.38	.23	1	2
GK	4.04	.63	1.40	.30	.37	.87	1	2
GL	3.21	.08	1.50	.39	.47	.15	1	2
HA	4.65	.14	2.20	.42	.54	.29	1	3
HB	4.42	.09	1.70	.39	.46	.19	1	2
HC	4.53	.19	1.50	.42	.48	.19	1	2
HD	4.23	.16	3.40	.70	.56	.28	1	2
HE	4.05	.15	3.50	.68	.54	.27	1	2
HF	3.85	.01	1.00	.29	.31	.08	1	2
HG	3.02	.06	1.10	.27	.34	.15	1	3

Lake ID	SO4 mg/l	Cl mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cu µg/l	Ni µg/l
HH	3.12	.05	1.80	.45	.53	.23	1	2
IA	3.53	.11	1.70	.44	.44	.40	1	2
IB	3.13	.09	1.80	.42	.44	.19	1	2
IC	3.39	.11	1.50	.37	.42	.32	1	2
ID	3.13	.10	2.20	.40	.36	.07	6	2
IE	3.04	.08	2.00	.43	.41	.24	1	2
IF	4.74	.06	3.80	.67	.85	.23	1	2
IG	4.68	.08	1.60	.39	.49	.17	1	2
IH	4.13	.25	2.40	.55	.65	.25	1	2
II	4.16	.25	2.40	.51	.63	.24	1	2
JA	4.93	.21	2.70	.40	.43	.29	1	2
JB	2.77	.20	1.90	.46	.47	.31	1	2
JC	2.95	.06	1.60	.31	.41	.25	1	2
JD	3.10	.07	2.80	.42	.45	.19	1	2
JE	4.01	.10	4.20	.42	.41	.22	11	2
JF	3.88	.01	2.80	.42	.33	.12	1	2
JG	3.88	.01	1.60	.30	.44	.11	1	2
JH	4.13	.01	4.00	.56	.57	.13	1	2
KA	4.90	.23	2.60	.40	.42	.29	1	2
KB	4.79	.23	2.90	.41	.42	.27	1	2
KC	3.78	.19	3.10	.59	.64	.45	1	2
KD	2.91	.10	2.90	.40	.40	.17	9	2
KE	3.39	.11	5.60	.39	.35	.20	10	3
KF	4.14	.08	4.70	.38	.38	.22	1	2
KG	4.31	.03	4.80	.50	.45	.20	1	2
KH	3.61	.01	2.20	.41	.43	.11	1	2
KI	3.71	.05	1.80	.34			1	2
KJ	4.58	.01	2.10	.37	.40	.13	1	2
KK	4.61	.01	2.20	.37	.46	.17	1	2
LA	4.48	.20	4.80	.46	.38	.23	1	2
LB	2.94	.15	7.00	.56	.44	.27	1	2
LC	3.97	.15	5.30	.32	.34	.14	1	2
LD	4.10	.03	4.90	.45	.31	.18	1	2
LE	4.38	.01	6.80	.43	.45	.22	1	2
LF	4.01	.01	2.70	.42	.57	.22	1	2
LG	4.38	.01	4.20	.42	.47	.22	1	2
LH	4.44	.03	4.30	.45	.48	.23	1	2
LI	3.77	.01	1.40	.27	.41	.18	1	2
LJ	5.07	.01	3.70	.47	.53	.27	1	2
LK	5.04	.14	3.60	.44	.54	.27	1	2

Lake ID	SO4 mg/l	Cl mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cu µg/l	Ni µg/l
LL	5.11	.17	3.60	.49	.51	.28	1	2
LM	2.38	.11	5.20	.40	.35	.17	1	2
LN	3.69	.17	6.10	.43	.39	.30	1	2
MA	2.60	.14	1.40	.31	.38	.30	1	7
MB	5.04	.13	4.20	.54	.50	.22	1	2
MC	5.04	.09	4.00	.56	.50	.22	1	2
MD	5.04	.09	4.10	.56	.49	.22	1	2
ME	5.17	.05	4.50	.42	.37	.20	1	2
MF	4.46	.05	2.30	.35	.34	.12	1	2
MG	5.11	.15	3.50	.47	.50	.26	1	2
NA	5.10	.39	2.50	.51	.66	.19	1	3
NB	4.42	.24	2.70	.53	.63	.27	1	2
NC	5.07	.09	4.00	.55	.45	.23	1	2
ND	4.90	.05	1.70	.42	.42	.22	1	2
NE	4.43	.08	1.80	.49	.49	.32	1	2
NF	4.68	.08	1.90	.47	.43	.22	1	2
NG	4.85	.09	1.90	.37	.37	.23	1	2
NH	4.39	.09	6.70	.67	.55	.27	1	2
NI	4.90	.06	3.70	.40	.47	.17	1	2
NJ	5.48	.07	4.60	.47	.50	.15	1	2
NK	5.65	.10	5.40	.42	.49	.17	1	2
NL	4.50	.01	2.60	.34	.32	.06	1	2
OA	4.37	.18	1.80	.27	.59	.09	2	2
OB	3.82	.14	1.30	.37	.44	.44	1	2
OC	4.91	.25	4.30	.60	.60	.20	1	2
OD	4.53	.17	4.00	.78	.64	.23	1	2
OE	5.21	.09	6.00	.70	.56	.26	1	2
OF	5.17	.15	5.60	.78	.63	.22	1	2
OG	3.58	.05	6.40	.68	.47	.17	1	2
OH	2.60	.05	5.40	.63	.48	.15	1	2
OI	3.78	.03	7.60	.59	.49	.11	1	2

Lake ID	Zn µg/l	Al µg/l	Mn µg/l	Fe µg/l	Total Chlor. *a* µg/l	Corr. Chlor. *a* µg/l	Chlor. *b* µg/l	Secchi Depth m	Bottom Depth m
AA	5	22	11	22	1.9	1.4	.5	5.2	12.0
AB	6	200	30	160	1.2	.3	.4	2.4	3.5
AC	7	210	31	87	2.2	.3	.4	3.0	15.9
AD	9	240	32	130	2.1	.2	.5	2.6	14.0
AE	8	250	54	72	1.4	.1	.2	5.6	13.6
AF	7	190	31	100	1.2	.4	.3	3.7	4.7
AG	7	160	38	41	1.2	.7	.2	4.8	12.2
AH	7	100	51	17	1.2	.8	.1	4.5	16.9
BA	6	220	50	130	2.1	1.2	.6	2.3	2.3
BB	7	130	33	22	1.2	.2	.3	6.0	6.0
BC	3	100	6	84	.6	.4	.2	2.5	6.3
BD	7	210	44	60	1.9	1.1	.3	2.9	2.9
BE	11	420	35	150	2.6	.2	.8	1.2	1.2
BF	2	100	4	100	.9	.5	.3	3.5	
BG	9	190	41	92	1.9	.9	.4	3.8	11.8
BH	6	120	51	24	1.1	.9	.1	5.5	18.0
BI	7	270	32	79	3.6	1.4	.6	2.5	14.2
CA	8	190	44	170	1.7	.4	.7	2.4	10.1
CB	6	160	24	65	2.2	.7	.8	4.2	6.0
CC	8	200	48	160	2.1	.2	.6	2.9	5.4
CD	8	190	44	100	2.0	.7	.9	3.3	10.2
CE	6	160	29	80	2.6	1.1	.8	3.8	13.6
CF	5	95	24	40	1.7	.7	.6	4.0	5.2
CG	6	300	39	550	5.4	1.9	2.7	2.5	6.5
CH	6	140	35	540	2.7	1.2	1.1	3.7	8.9
CI	7	380	37	130	3.6	1.0	1.5	1.4	9.9
CJ	10	140	38	26	2.9	1.2	.8	5.5	12.0
CK	6	180	15	52	1.5	.5	.5	1.8	1.8
DA	11	280	40	180	2.0	.4	.7	2.5	8.3
DB	11	480	27	360	3.5	.7	1.1	.4	.4
DC	9	250	48	170	2.6	.5	1.0	1.8	9.4
DD	9	130	35	60	2.8	1.0	.6	3.8	7.2
DE	10	100	43	420	1.7	.7	.6	4.8	6.2
DF	6	87	53	61	.8	.4	.3	8.5	11.9
DG	6	110	50	25	1.0	.7	.5	6.0	12.6
DH	7	83	54	19	.7	.4	.2	4.9	4.9
DI	6	220	40	93	2.9	1.0	.7	3.7	15.0
DJ	5	200	21	67	1.6	.6	.6	3.5	3.8
EA	13	390	38		2.1	.7	.4	4.3	7.2
EB	10	280	49	120	2.7	1.0	.8	2.7	5.2

Lake ID	Zn µg/l	Al µg/l	Mn µg/l	Fe µg/l	Total Chlor. *a* µg/l	Corr. Chlor. *a* µg/l	Chlor. *b* µg/l	Secchi Depth m	Bottom Depth m
EC	9	200	33	96	2.6	1.1	.8	2.6	2.6
ED	9	120	34	43	2.7	1.1	.8	3.9	15.5
EE	5	68	31	94	1.8	.4	.7	6.2	7.4
EF	9	340	34	200	2.1	.6	.8	2.5	2.5
EG	7	250	36	58	2.8	1.5	.7	3.8	6.4
EH	7	150	40	57	1.4	.3	.4	4.7	16.5
EI	8	150	35	58	2.3		.9	5.3	5.3
EJ	9	310	26	66	1.8	.6	.9	3.8	11.6
EK	5	180	17	140	2.5	1.1	1.0	1.3	1.3
EL	9	380	35	110	1.4	.4	.4	2.4	5.3
FA	9	150	40	32	1.3	.2	.2	7.0	15.5
FB	10	330	32	92	1.7	.6	.5	3.5	16.0
FC	8	220	38	130				3.0	9.9
FD	6	250	18	210	6.0	.4	1.9	.9	1.5
FE	7	170	41	93	1.5	.2	.5	4.2	6.3
FF	7	150	39	77	2.0	.3	.6	4.5	19.0
FG	4	79	14	91	1.7	.3	.5	1.0	1.0
FH	1	55	6	51	2.1	1.1	.5	3.2	15.0
FI	3	110	17	45	4.0	2.1	.8	3.6	3.6
FJ	10	490	28	160	2.9	.7	.7	1.1	1.1
FK	10	240	28	41	2.1	1.2	.7	1.4	1.4
GA	5	28	5	8	1.3	.4	.3	7.7	10.3
GB	10	230	37	100	1.5	.5	.4	3.4	3.4
GC	8	150	51	100	1.1	.4	.5	6.8	10.9
GD	10	250	36	220	1.2	.6	.4	4.0	9.5
GE	8	200	31	84	1.2	.4	.3	3.7	4.5
GF	7	65	32	22	3.6	1.4	1.1	6.9	7.4
GG	4	150	20	52	1.4	.0	.5	3.0	3.0
GH	7	260	35	230	2.6	.6	.8	2.5	6.0
GI	3	38	11	37	1.6	.1	.6	3.8	3.8
GJ	6	59	14	30	2.4	.7	1.0	4.6	12.8
GK	3	31	10	22	2.7	1.2	.9	4.7	6.7
GL	6	230	15	170	2.0	.6	.5	2.5	4.5
HA	4	79	24	65	1.8	1.2	.5	2.0	2.0
HB	9	62	8	44	1.8	1.0	.5	5.5	6.2
HC	5	67	8	41	1.7	.6	.3	5.0	13.6
HD	2	30	10	100	2.6	1.6	.7	2.9	3.7
HE	2	84	19	140	17.0	14.1	2.1	2.0	3.0
HF	7	140	36	72	1.7	.5	.7	1.4	1.4
HG	7	230	39	310	4.9	1.3	1.5	1.6	2.9

Lake ID	Zn µg/l	Al µg/l	Mn µg/l	Fe µg/l	Total Chlor. *a* µg/l	Corr. Chlor. *a* µg/l	Chlor. *b* µg/l	Secchi Depth m	Bottom Depth m
HH	4	210	13	150	4.5	2.0	.9	1.3	1.3
IA	6	90	24	83	4.4	2.1	1.1	2.4	12.3
IB	5	150	29	340	2.5	.9	.8	1.6	4.3
IC	5	100	71	430	10.0	6.7	13.3	2.6	6.7
ID	8	290	21	260	2.3	.6	1.1	.4	.4
IE	6	280	21	270	4.8	2.1	1.4	1.1	11.9
IF	3	74	7	77	2.3	1.5	.8	1.4	1.4
IG	4	75	11	32	2.4	1.3	.8	4.8	6.1
IH	3	88	12	130	4.1	2.1	.8	2.6	2.6
II	3	91	12	130	4.3	2.8	.8	2.4	2.4
JA	8	52	5	6	1.4	.4	.4	7.0	8.2
JB	6	210	31	280	4.4	2.7	1.1	.9	20.0
JC	4	150	14	350	4.3	1.9	1.6	.9	.9
JD	2	110	18	120	2.2	1.2	.7	2.2	8.6
JE	3	79	8	37	2.0	1.0	.6	1.8	11.3
JF	3	58	5	69	3.6	1.5	.9	2.0	5.3
JG	5	190	24	83	2.2	.3	1.1	1.8	1.8
JH	3	100	5	41	1.6	.8	.4	2.0	2.0
KA	4	49	2	8	1.5	1.0	.4	7.4	14.4
KB	4	54	9	13	1.8	.8	.4	5.2	7.0
KC	3	100	15	110	3.8	2.0	.9	2.0	3.0
KD	3	120	16	150	2.8	1.8	.9	3.5	20.0
KE	2	65	5	69	3.2	1.6	.9	2.9	8.9
KF	2	53	13	63	2.7	1.9	.5	2.9	6.8
KG	1	71	5	39	3.6	2.7	.4	4.0	19.0
KH	4	180	18	100	3.9	3.1	.8	2.2	5.0
KI	6	230	24	130	4.2	1.8	.9	1.8	8.2
KJ	3	140	7	30	1.0	.9	.2	4.5	4.5
KK	1	45	8	11	1.4	1.0	.2	5.9	8.9
LA	3	35	7	13	2.4	.9	.6	4.2	4.2
LB	4	97	14	120	4.8	2.6	.7	2.0	2.0
LC	4	68	8	38	2.3	1.2	.8	2.7	3.4
LD	2	64	5	48	4.5	1.5	.7	2.4	2.4
LE	1	10	8	9	1.8	1.4	.4	6.5	10.4
LF	2	36	7	35	3.4	2.1	.3	4.3	9.2
LG	1	34	4	17	2.7	1.6	.4	5.1	17.4
LH	1	34	4	22	2.8	2.2	.4	4.9	9.9
LI	1	82	12	34	3.6	2.2	.6	4.6	11.4
LJ	2	21	3	5	.6	.4	.1	10.5	15.8
LK	1	23	3	7	.6	.4	.1	10.2	16.0

Lake ID	Zn µg/l	Al µg/l	Mn µg/l	Fe µg/l	Total Chlor. *a* µg/l	Corr. Chlor. *a* µg/l	Chlor. *b* µg/l	Secchi Depth m	Bottom Depth m
LL	1	30	1	6	.7	.4	.1	9.9	10.0
LM	2	110	13	200	1.2	.1	.3	1.2	4.3
LN	1	34	11	46	4.2	3.2	.8	2.3	8.3
MA	7	230	27	210	3.7	1.6	1.2	1.6	2.5
MB	1	19	6	14	4.1	2.6	.9	5.4	15.0
MC	1	20	3	9	3.9	2.9	.7	5.8	20.0
MD	1	20	4	14	3.3	2.2	.6	6.0	6.8
ME	1	25	4	28	2.0	1.0	.2	3.6	3.6
MF	4	58	6	41	.9	.5	.2	4.8	10.8
MG	1	34	2	11	.5	.2	.2	4.4	4.4
NA	7	76	3	25	1.5	.5	.4	6.8	15.4
NB	4	28	9	14	3.8	2.3	.6	4.9	6.2
NC	1	21	4	13	3.3	2.5	.7	5.8	20.0
ND	5	47	6	16	2.4	1.5	.5	5.5	5.5
NE	3	39	11	37	3.6	2.3	.5	5.0	14.2
NF	2	18	7	28	1.1	.6	.3	5.8	18.0
NG	2	12	3	5	3.6	2.2	.6	6.7	11.8
NH	4	55	64	700	15.1	11.3	7.2	1.4	5.8
NI	2	53	18	66	5.3	3.9	.9	2.8	4.5
NJ	2	36	5	14	1.4	1.1	.2	5.6	11.5
NK	2	29	3	10	1.8	1.1	.3	5.9	7.3
NL	8	150	6	68	1.5	.3	.6	1.5	1.5
OA	10	200	12	30	1.3	.6	.4	1.5	1.5
OB	6	130	20	49	2.7	1.2	.6	3.4	12.2
OC	2	49	6	57	1.2	.4	.6	3.5	3.5
OD	1	38	7	57	3.6	2.4	.9	2.5	4.0
OE	2	39	8	49	6.6	3.5	1.2	2.0	2.3
OF	2	47	16	60	4.4	2.5	1.1	2.8	8.5
OG	3	84	12	120	1.5	.6	.7	1.9	1.9
OH	3	97	9	150	1.4	.1	.7	1.2	1.2
OI	3	60	4	67	1.0	.1	.6	.8	.8

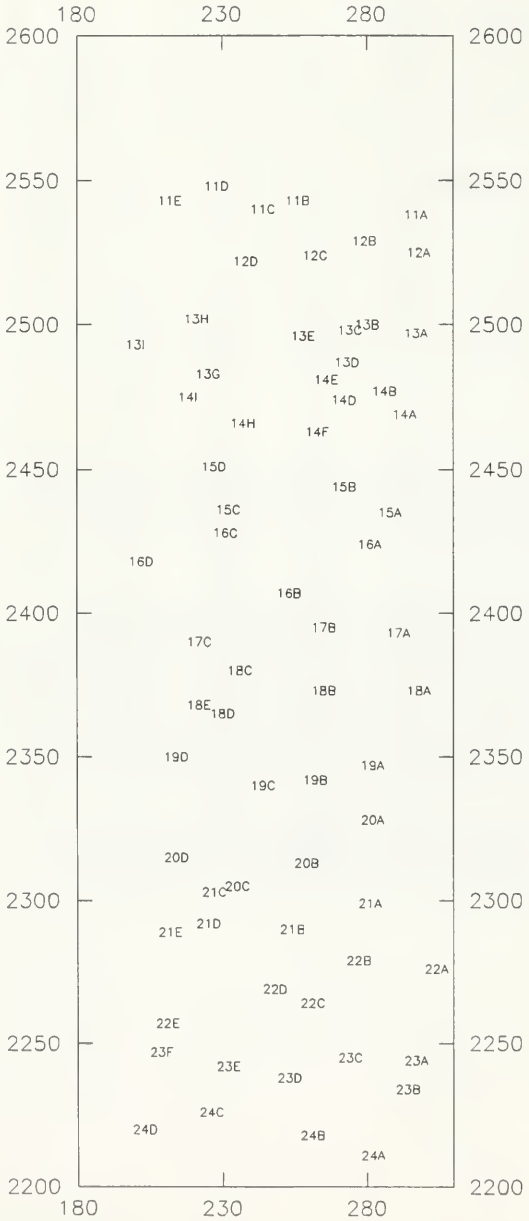
APPENDIX E

SURFACE WATER CHEMISTRY OF THE SUDBURY STUDY LAKES

This appendix lists the lake chemistry data that were acquired in August 1986 specifically for this remote sensing project (see Section 2.2 for sampling and analytical methodologies).

The locations of the lake sampling sites have been identified by both geographic (latitude/longitude) and universal transverse Mercator (UTM) coordinates, the latter to the nearest hundredth meter. The tables list the UTM coordinates in an abbreviated form. For example for Madden Lake at 256E 2538N, the full UTM reference would be: 17 T 525600 5253800. These lakes can be found on the Sudbury (41I) and Gogama (41P) National Topographic Survey maps (1:250,000).

Maps (for the northern and southern sections of the study area) of the lake site locations, using the shortened UTM coordinates, are provided overleaf.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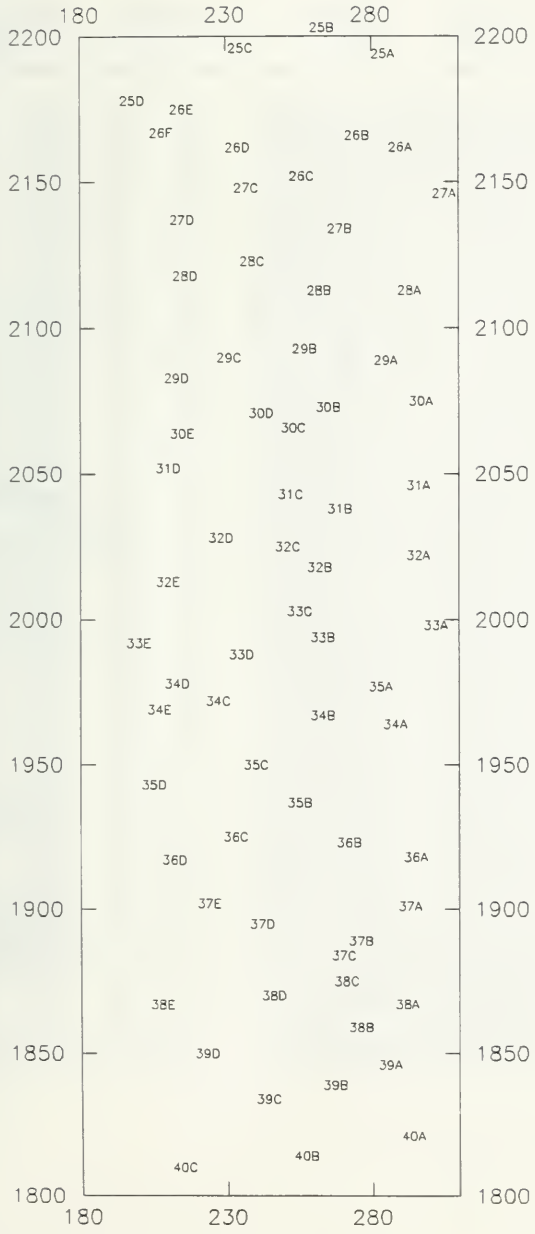
Sudbury (N)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40C

Sudbury (S)

ID	Lake Name	Sampling Date	UTM Grid E	UTM Grid N	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min
11A		26/8/1986	297	2533	47	26	80	36
11B	MADDEN	26/8/1986	256	2538	47	26	80	40
11C	LAMY	26/8/1986	244	2535	47	26	80	41
11D	LADY DUFFERIN	26/8/1986	228	2543	47	27	80	42
11E		26/8/1986	212	2538	47	26	80	43
12A	WABUN	26/8/1986	298	2520	47	25	80	36
12B		26/8/1986	279	2524	47	26	80	38
12C		26/8/1986	262	2519	47	25	80	39
12D	SMOOTHWATER	26/8/1986	238	2517	47	25	80	41
13A	SUNNYWATER	26/8/1986	297	2492	47	24	80	36
13B	SUNNYWATER	26/8/1986	280	2495	47	24	80	38
13C		26/8/1986	274	2493	47	24	80	38
13D	WHITEPINE	16/8/1986	273	2482	47	23	80	38
13E	MARINA	26/8/1986	258	2491	47	24	80	40
13G	SMOOTHWATER	26/8/1986	225	2478	47	23	80	42
13H		26/8/1986	221	2497	47	24	80	42
13I		26/8/1986	201	2488	47	24	80	44
14A	LITTLE AURORA	16/8/1986	293	2464	47	22	80	37
14B	WHITEPINE	16/8/1986	286	2472	47	23	80	37
14D	WHIRLIGIG	16/8/1986	272	2469	47	23	80	38
14E	LITTLE WHITEPINE	16/8/1986	266	2476	47	23	80	39
14F	JERRY	16/8/1986	263	2458	47	22	80	39
14H	SMOOTHWATER	16/8/1986	237	2461	47	22	80	41
14I		16/8/1986	219	2470	47	23	80	43
15A		16/8/1986	288	2430	47	21	80	37
15B		16/8/1986	272	2439	47	21	80	38
15C		16/8/1986	232	2431	47	21	80	42
15D	APEX	16/8/1986	227	2446	47	21	80	42
16A		16/8/1986	281	2419	47	20	80	38
16B		16/8/1986	253	2402	47	19	80	40
16C		16/8/1986	231	2423	47	20	80	42
16D		16/8/1986	202	2413	47	20	80	44
17A		16/8/1986	291	2388	47	18	80	37
17B		16/8/1986	265	2390	47	18	80	39
17C	MIHELL	16/8/1986	222	2385	47	18	80	43
18A		16/8/1986	298	2368	47	17	80	36
18B	NORTH YORSTON	16/8/1986	265	2368	47	17	80	39
18C		16/8/1986	236	2375	47	18	80	41
18D		16/8/1986	230	2360	47	17	80	42
18E		11/8/1986	222	2363	47	17	80	42

ID	Lake Name	Sampling Date	UTM Grid E	UTM Grid N	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min
19A		16/8/1986	282	2342	47	16	80	38
19B		16/8/1986	262	2337	47	16	80	39
19C		11/8/1986	244	2335	47	15	80	41
19D		11/8/1986	214	2345	47	16	80	43
20A		11/8/1986	282	2323	47	15	80	38
20B		11/8/1986	259	2308	47	14	80	40
20C		11/8/1986	235	2300	47	14	80	41
20D		11/8/1986	214	2310	47	14	80	43
21A		11/8/1986	281	2294	47	13	80	38
21B	PILGRIM	11/8/1986	254	2285	47	13	80	40
21C		11/8/1986	227	2298	47	13	80	42
21D		16/8/1986	225	2287	47	13	80	42
21E		16/8/1986	212	2284	47	13	80	43
22A		11/8/1986	304	2271	47	12	80	36
22B		11/8/1986	277	2274	47	12	80	38
22C	PILGRIM	11/8/1986	261	2259	47	11	80	39
22D	MAGGIE	11/8/1986	248	2264	47	12	80	40
22E		11/8/1986	211	2252	47	11	80	43
23A	BLUESUCKER	9/8/1986	297	2239	47	10	80	37
23B		9/8/1986	294	2229	47	10	80	37
23C	RODD	9/8/1986	274	2240	47	10	80	38
23D		9/8/1986	253	2233	47	10	80	40
23E	SOLACE	11/8/1986	232	2237	47	10	80	42
23F		11/8/1986	209	2242	47	10	80	44
24A		9/8/1986	282	2206	47	9	80	38
24B		9/8/1986	261	2213	47	9	80	39
24C		11/8/1986	226	2221	47	9	80	42
24D		11/8/1986	203	2215	47	9	80	44
25A		9/8/1986	284	2189	47	8	80	38
25B	MUCK	9/8/1986	263	2198	47	8	80	39
25C		11/8/1986	235	2191	47	8	80	42
25D		11/8/1986	198	2173	47	7	80	44
26A		9/8/1986	290	2157	47	6	80	37
26B	LIMIT	9/8/1986	275	2161	47	6	80	38
26C	HAZEL	9/8/1986	256	2147	47	5	80	40
26D	MUDDING	11/8/1986	234	2157	47	6	80	42
26E		11/8/1986	215	2170	47	7	80	43
26F		11/8/1986	208	2162	47	6	80	44
27A		9/8/1986	305	2141	47	5	80	36
27B	STURGEON RIVER	9/8/1986	269	2129	47	4	80	39

ID	Lake Name	Sampling Date	UTM Grid E	UTM Grid N	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min
27C	PUDDLE	11/8/1986	237	2143	47	5	80	41
27D		11/8/1986	215	2132	47	4	80	43
28A	STURGEON RIVER	9/8/1986	293	2108	47	3	80	37
28B		9/8/1986	262	2108	47	3	80	39
28C	STOUFFER	11/8/1986	239	2118	47	4	80	41
28D		11/8/1986	216	2113	47	3	80	43
29A		9/8/1986	285	2084	47	2	80	38
29B		9/8/1986	257	2088	47	2	80	40
29C	FREDERICK	9/8/1986	231	2085	47	2	80	42
29D		9/8/1986	213	2078	47	2	80	43
30A		8/8/1986	297	2070	47	1	80	37
30B	DOUGHERTY	8/8/1986	265	2068	47	1	80	39
30C	DOUGHERTY	8/8/1986	253	2061	47	1	80	40
30D		8/8/1986	242	2066	47	1	80	41
30E		8/8/1986	215	2059	47	1	80	43
31A		8/8/1986	296	2041	46	60	80	37
31B	ADELAIDE	8/8/1986	269	2033	46	59	80	39
31C		8/8/1986	252	2038	46	59	80	40
31D		8/8/1986	210	2047	46	60	80	43
32A		8/8/1986	296	2017	46	58	80	37
32B	CHINIGUCHI	8/8/1986	262	2013	46	58	80	39
32C		8/8/1986	251	2020	46	58	80	40
32D		8/8/1986	228	2023	46	59	80	42
32E		8/8/1986	210	2008	46	58	80	44
33A	LAURA	8/8/1986	302	1993	46	57	80	36
33B	CHINIGUCHI(McC.BAY)	8/8/1986	263	1989	46	57	80	39
33C	CHINIGUCHI(McC.BAY)	8/8/1986	255	1998	46	57	80	40
33D	CHINIGUCHI	8/8/1986	235	1983	46	56	80	42
33E		8/8/1986	200	1987	46	57	80	44
34A		8/8/1986	288	1959	46	55	80	37
34B		8/8/1986	263	1962	46	55	80	39
34C	CHINIGUCHI	8/8/1986	227	1967	46	56	80	42
34D		8/8/1986	213	1973	46	56	80	43
34E		8/8/1986	207	1964	46	55	80	44
35A		8/8/1986	283	1972	46	56	80	38
35B	DEWDNEY	8/8/1986	255	1932	46	54	80	40
35C	CHINIGUCHI(SE BAY)	8/8/1986	240	1945	46	54	80	41
35D		8/8/1986	205	1938	46	54	80	44
36A		8/8/1986	295	1913	46	53	80	37
36B	FRANKS	8/8/1986	272	1918	46	53	80	39

ID	Lake Name	Sampling Date	UTM Grid E	UTM Grid N	Latitude Deg	Latitude Min	Longitude Deg	Longitude Min
36C	CHINIGUCHI	8/8/1986	233	1920	46	53	80	42
36D	LAWLOR	8/8/1986	212	1912	46	53	80	43
37A		7/8/1986	293	1896	46	52	80	37
37B	WOLF	7/8/1986	276	1884	46	51	80	38
37C	SILVESTER	7/8/1986	270	1879	46	51	80	39
37D		7/8/1986	242	1890	46	51	80	41
37E		7/8/1986	224	1897	46	52	80	42
38A		7/8/1986	292	1862	46	50	80	37
38B	MATAGAMASI	7/8/1986	276	1854	46	49	80	38
38C	SILVESTER	7/8/1986	271	1870	46	50	80	39
38D	OTTER	7/8/1986	246	1865	46	50	80	41
38E		7/8/1986	208	1862	46	50	80	44
39A	MATAGAMASI	7/8/1986	286	1841	46	49	80	38
39B	THOMAS	7/8/1986	267	1834	46	48	80	39
39C		7/8/1986	244	1829	46	48	80	41
39D		7/8/1986	223	1845	46	49	80	43
40A	MATAGAMASI	7/8/1986	294	1816	46	47	80	37
40B	RATHBUN	7/8/1986	257	1809	46	47	80	40
40C	WANAPITEI	7/8/1986	215	1805	46	47	80	43

Lake ID	pH	TFE ALK pH4.5 mg/l	TFE ALK pH3.8 mg/l	TIP ALK mg/l	COND. µmos/cm	Kjeld. N mg/l	TOTAL P mg/l	SUSP. SOLIDS mg/l	DOC (C) mg/l
11A	4.66	.62	7.62	-1.10	31	.17	.004	1	3.3
11B	4.65	.62	7.55	-1.10	33	.13	.002	1	2.5
11C	6.19	2.64	9.67	.83	29	.11	.003	1	2.3
11D	6.89	6.03	13.00	4.19	37	.14	.005	1	2.4
11E	4.73	.86	7.92	-.90	32	.71	.021	1	4.4
12A	4.93	1.25	8.20	-.55	29	.08	.001	1	1.1
12B	4.70	.78	7.73	-.99	31	.05	.002	1	.3
12C	4.40	.00	7.14	-2.16	36	.34	.011	2	6.2
12D	6.49	3.20	10.23	1.39	33	.12	.002	1	1.7
13A	4.68	.71	7.76	-1.10	36	.08	.001	1	.4
13B	4.69	.71	7.95	-1.09	36	.07	.001	1	.2
13C	4.62	.49	7.63	-1.32	36	.10	.003	1	.6
13D	4.98	1.35	8.38	-.44	30	.12	.004	1	1.6
13E	5.47			.00	29	.16	.009	1	1.9
13G	6.17	2.43	9.54	.61	32	.09	.002	1	1.4
13H	5.55	1.98	9.27	.11	29	.16	.034	1	2.4
13I	4.75	.89	8.07	-.94	30	.16	.003	1	1.9
14A	5.16	1.61	8.83	-.23	31	.31	.005	1	2.8
14B	5.01	1.45	8.70	-.45	31	.12	.004	1	1.6
14D	4.90	1.24	8.55	-.61	29	.16	.005	1	2.4
14E	5.44	1.86	9.30	-.07	26	.16	.003	1	2.0
14F	5.14			-.03	33	.06	.001	1	.4
14H	6.18	2.46	10.02	.56	33	.08	.002	1	1.4
14I	4.97	1.37	8.74	-.49	30	.22	.007	1	3.1
15A	5.06	1.54	9.04	-.39	37	.04	.001	1	.3
15B	4.64	.63	8.30	-1.24	34	.14	.002	1	1.9
15C	6.76	7.42	15.07	5.47	42	.13	.003	1	1.9
15D	6.85	7.07	14.65	5.09	39	.23	.005	2	2.3
16A	6.84	4.27	12.05	2.29	42	.38	.010	2	5.1
16B	4.39	.00	6.68	-2.17	40	.27	.005	1	2.8
16C	6.66	3.89	11.41	1.98	33	.11	.002	1	1.9
16D	4.74	.92	8.49	-.97	34	.08	.004	1	.7
17A	4.80	1.03	8.02	-.73	33	.06	.001	1	.3
17B	5.02	1.52	8.81	-.34	38	.25	.005	1	3.8
17C	7.38	13.94	21.22	12.05	54	.15	.004	1	2.5
18A	4.30	.00	6.27	-2.66	41	.32	.008	1	3.9
18B	5.25	1.68	8.86	-.17	32	.09	.001	1	1.3
18C	4.30	.00	6.41	-2.73	44	.28	.008	1	5.0
18D	4.64	.61	7.99	-1.17	35	.13	.002	1	1.6
18E	4.61	.53	7.74	-1.26	38	.11	.017	1	2.2

Lake ID	pH	TFE ALK pH4.5 mg/l	TFE ALK pH3.8 mg/l	TIP ALK mg/l	COND. µmos/cm	Kjeld. N mg/l	TOTAL P mg/l	SUSP. SOLIDS mg/l	DOC (C) mg/l
19A	4.94	1.35	8.62	-.51	33	.12	.001	1	1.7
19B	5.43	1.84	9.02	-.06	32	.16	.003	1	2.0
19C	5.51	1.76	8.78	-.04	28	.12	.007	1	1.6
19D	4.60	.45	7.68	-1.33	40	.08	.008	1	.7
20A	4.40	.00	6.60	-2.16	39	.08	.003	1	.2
20B	4.77	.89	7.89	-.88	34	.16	.006	1	3.6
20C	5.72	3.17	10.62	1.45	28	.39	.016	1	10.3
20D	5.52	1.82	8.46	.11	33	.15	.007	1	2.8
21A	4.58	.39	7.26	-1.27	38	.05	.004	1	.2
21B	5.46	1.76	8.28	.06	28	.17	.012	1	2.3
21C	5.69	2.01	8.61	.30	31	.12	.006	1	2.1
21D	5.99	2.59	9.90	.74	34	.49	.007	1	2.3
21E	5.68	2.07	9.19	.30	31	.16	.006	1	2.4
22A	6.26	3.24	9.68	1.58	34	.29	.007	1	2.6
22B	6.07	2.45	8.98	.77	33	.19	.004	1	2.3
22C	5.46	1.70	8.22	-.01	27	.13	.003	1	2.2
22D	6.67	4.21	11.31	2.36	38	.14	.009	1	2.2
22E	5.65	2.06	9.15	.27	30	.21	.008	1	3.8
23A	5.53	1.88	8.84	.11	33	.10	.009	1	1.7
23B	4.43	.00	6.54	-1.96	40	.22	.008	2	.9
23C	5.87	2.20	9.23	.43	29	.21	.006	1	2.7
23D	4.63	.56	7.65	-1.17	35	.30	.008	2	4.5
23E	5.70	1.98	9.04	.25	31	.14	.009	1	2.4
23F	5.79	2.17	9.26	.39	30	.22	.008	3	3.4
24A	5.26	2.71	10.48	.99	34	.61	.009	3	15.9
24B	5.69	2.07	9.00	.25	30	.19	.007	2	3.2
24C	4.92	1.39	8.66	-.48	31	.30	.012	3	5.6
24D	6.29	3.73	10.79	1.92	34	.38	.011	1	4.8
25A	6.23	4.27	11.26	2.48	33	.23	.008	1	4.8
25B	5.80	2.61	9.70	.80	31	.24	.006	1	5.1
25C	4.87	1.08	7.99	-.66	34	.19	.004	1	2.1
25D	6.58	5.60	12.73	3.85	34	.38	.013	2	4.5
26A	6.44	4.72	11.89	2.93	34	.25	.008	2	5.5
26B	6.07	4.55	12.17	2.79	31	.50	.015	4	10.5
26C	7.40	20.25	27.96	18.48	64	.26	.008	2	7.0
26D	5.82	2.20	9.13	.43	29	.19	.003	1	3.6
26E	6.00	2.22	8.99	.44	33	.13	.004	1	1.7
26F	4.77	.87	7.90	-.88	35	.19	.014	1	3.4
27A	7.61	20.83	28.41	18.90	109	.10	.005	1	1.8
27B	7.40	19.54	27.31	17.76	63	.26	.007	1	6.9

Lake ID	pH	TFE ALK pH4.5 mg/l	TFE ALK pH3.8 mg/l	TIP ALK mg/l	COND. µmos/cm	Kjeld. N mg/l	TOTAL P mg/l	SUSP. SOLIDS mg/l	DOC (C) mg/l
27C	5.48	2.26	9.50	.46	29	.31	.012	10	7.0
27D	5.02	1.37	8.44	-.43	29	.25	.007	1	3.6
28A	7.32	19.17	26.83	17.36	63	.27	.010	3	5.8
28B	4.21	.00	5.68	-3.39	40	.38	.014	2	9.3
28C	4.99	1.13	8.40	-.48	37	.13	.008	1	1.8
28D	5.57	1.97	8.97	.12	32	.17	.008	1	3.1
29A	6.43	5.18	12.88	3.37	43	.43	.011	2	8.0
29B	4.43	.00	6.85	-2.00	30	.30	.010	3	4.0
29C	4.75	.84	7.82	-.93	41	.08	.002	1	.6
29D	7.03	7.09	14.07	5.26	34	.17	.006	1	2.0
30A	4.95	1.38	8.59	-.47	38	.80	.012	3	5.6
30B	4.61	.44	7.45	-1.29	44	.08	.003	1	.8
30C	4.63	.55	7.62	-1.27	43	.07	.003	1	.8
30D	4.38	.00	6.06	-2.01	37	.28	.008	1	2.9
30E	5.03			-.32	30	.19	.005	1	2.5
31A	5.69	2.78	9.92	.99	35	.26	.010	2	5.2
31B	7.16	9.96	16.81	8.23	44	.25	.011	1	2.4
31C	5.97	2.47	9.02	.81	34	.20	.008	1	3.6
31D	6.94	6.60	13.23	4.93	40	.17	.005	1	2.9
32A	5.95	2.26	9.05	.54	34	.16	.003	1	2.7
32B	5.12	1.49	8.32	-.28	37	.07	.002	1	.8
32C	5.98	2.80	9.82	1.00	35	.18	.011	1	3.8
32D	4.91	1.27	8.19	-.49	33	.18	.006	1	3.2
32E	4.98	1.29	7.91	-.41	33	.09	.003	1	.8
33A	6.24	2.46	9.29	.73	42	.12	.005	1	2.4
33B	4.54	.17	7.20	-1.51	41	.05	.004	1	.3
33C	4.54	.22	7.25	-1.49	41	.07	.002	1	.3
33D	4.86	1.06	7.69	-.62	38	.06	.002	1	.4
33E	4.98	1.28	8.01	-.43	33	.11	.004	1	.9
34A	4.39	.00	6.59	-2.13	42	.08	.004	1	.7
34B	4.44	.00	6.78	-1.91	41	.07	.004	1	.2
34C	4.85	1.08	7.84	-.65	38	.08	.003	1	.3
34D	4.40	.00	6.45	-2.06	38	.09	.002	1	.1
34E	4.40	.00	6.80	-2.14	40	.08	.004	1	.1
35A	4.41	.00	6.79	-2.04	43	.10	.005	1	.3
35B	4.73	.81	7.73	-.93	40	.07	.003	1	.5
35C	4.84			-.71	38	.09	.002	1	.5
35D	4.30	.00	6.06	-2.74	43	.07	.003	1	.2
36A	4.28	.00	6.12	-2.84	42	.25	.008	1	4.4
36B	4.59	.42	7.37	-1.30	43	.20	.007	1	.3

Lake ID	pH	TFE ALK pH4.5 mg/l	TFE ALK pH3.8 mg/l	TIP ALK mg/l	COND. µmos/cm	Kjeld. N mg/l	TOTAL P mg/l	SUSP. SOLIDS mg/l	DOC (C) mg/l
36C	4.60	.41	7.20	-1.26	46	.07	.001	1	.2
36D	4.51	.09	7.02	-1.54	40	.09	.002	1	.9
37A	4.26	.00		-3.00	45	.29	.009	1	3.2
37B	4.66	.61	7.51	-1.15	42	.06	.002	1	.7
37C	4.65	.59	7.56	-1.15	42	.09	.002	1	.8
37D	4.29	.00	6.08	-2.79	46	.14	.004	1	1.1
37E	5.17	1.53	8.48	-.25	38	.08	.003	1	.6
38A	4.58			-1.39	35	.12	.005	1	1.6
38B	4.63	.53	7.54	-1.22	42	.09	.002	1	.8
38C	4.64	.56	7.48	-1.18	40	.09	.002	1	.5
38D	4.34	.00	6.30	-2.46	54	.06	.001	1	.2
38E	6.15	4.95	12.13	3.14	39	.41	.009	1	4.9
39A	5.16			-.23	35	.22	.009	1	3.2
39B	6.24	3.48	10.53	1.66	37	.18	.006	1	3.8
39C	4.62	.51	7.49	-1.23	47	.20	.005	1	2.5
39D	4.75	.89	8.02	-.89	37	.23	.007	1	3.2
40A	4.84	1.06	8.03	-.72	39	.12	.004	1	1.4
40B	7.03	9.42	16.71	7.51	54	.23	.008	1	3.5
40C	7.53	17.20	24.71	15.33	69	.18	.003	1	4.1

Lake ID	SO4 mg/l	Cl mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cu µg/l	Ni µg/l
11A	8.73	.36	1.60	.55	.52	.55	1	2
11B	9.54	.17	1.60	.48	.49	.39	1	3
11C	9.73	.20	2.50	.77	.61	.44	1	3
11D	10.60	.22	3.50	1.10	.70	.40	1	2
11E	9.40	.01	1.80	.50	.48	.21	1	2
12A	9.32	.16	1.70	.50	.52	.35	1	4
12B	9.09	.10	1.30	.40	.45	.26	1	2
12C	9.07	.06	1.50	.42	.49	.16	1	5
12D	10.90	.15	2.90	.91	.65	.42	1	2
13A	10.90	.12	2.10	.50	.39	.37	2	4
13B	10.80	.12	2.00	.54	.42	.38	2	5
13C	10.70	.09	1.90	.53	.44	.32	2	2
13D	9.32	.21	1.90	.59	.64	.45	1	2
13E	9.84	.12	2.10	.70	.63	.35	1	3
13G	10.90	.22	2.70	.83	.71	.40	1	3
13H	9.95	.17	2.20	.68	.59	.46	1	2
13I	9.29	.09	1.60	.52	.55	.32	1	2
14A	9.41	.20	2.20	.67	.72	.46	1	2
14B	8.71	.38	1.90	.59	.64	.65	1	4
14D	8.12	.19	1.90	.54	.58	.39	1	5
14E	8.46	.24	1.90	.62	.49	.46	1	2
14F	10.50	.28	2.10	.60	.63	.51	1	2
14H	10.70	.33	3.00	.81	.69	.55	1	2
14I	9.27	.21	2.10	.56	.71	.48	1	2
15A	11.40	.28	2.30	.61	.67	.52	1	4
15B	9.86	.04	1.40	.39	.62	.23	1	4
15C	11.20	.39	4.00	1.30	.96	.65	2	3
15D	10.10	.29	3.70	1.20	.92	.53	1	2
16A	12.80	.23	3.40	1.20	1.60	.42	2	3
16B	10.90	.08	2.20	.48	.47	.30	1	6
16C	10.10	.30	2.80	.88	.75	.55	1	2
16D	10.10	.40	1.80	.43	.63	.67	1	4
17A	9.73	.48	1.70	.48	.53	.40	1	3
17B	11.90	.16	2.50	.88	.87	.50	1	6
17C	10.30	.20	5.70	1.76	.96	.70	1	3
18A	10.40	.44	1.60	.44	.53	.30	1	7
18B	10.50	.34	2.00	.67	.78	.72	1	4
18C	10.80	.15	1.40	.39	.52	.29	1	6
18D	9.88	.10	1.50	.44	.55	.30	1	5
18E	9.80	.85	1.70	.46	.49	1.21	1	5

Lake ID	SO4 mg/l	Cl mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cu µg/l	Ni µg/l
19A	10.20	.37	1.90	.54	.69	.61	1	6
19B	10.30	.46	2.40	.72	.92	.47	1	3
19C	8.85	.34	2.20	.58	.64	.50	1	2
19D	11.10	.50	1.80	.45	.55	.78	1	7
20A	9.91	.38	1.40	.32	.42	.50	1	6
20B	9.52	.47	2.10	.65	.63	.63	2	6
20C	6.92	.41	2.40	.75	.92	.51	1	2
20D	10.60	.41	2.40	.80	.72	.65	1	4
21A	10.60	.37	1.60	.42	.52	.56	1	4
21B	8.68	.28	1.90	.62	.66	.46	1	2
21C	10.30	.26	2.50	.76	.72	.56	1	4
21D	11.20	.32	2.70	.86	.76	.37	1	3
21E	9.72	.44	2.20	.73	.73	.69	1	5
22A	10.40	.24	2.60	.92	1.10	.46	2	3
22B	10.50	.41	2.80	.78	.82	.57	1	2
22C	8.71	.31	2.20	.65	.63	.47	1	3
22D	10.00	.71	2.70	.96	.82	.90	1	3
22E	9.13	.28	2.40	.67	.65	.54	1	3
23A	9.85	.75	2.00	.71	.76	1.08	1	3
23B	10.60	.47	1.80	.61	.50	.70	2	6
23C	9.09	.44	2.10	.71	.71	.52	1	2
23D	8.95	.27	1.80	.51	.58	.39	2	4
23E	10.40	.09	2.40	.73	.68	.47	1	4
23F	9.35	.02	2.40	.71	.68	.46	1	3
24A	8.13	.13	3.10	.91	.82	.18	2	3
24B	9.88	.21	2.30	.76	.66	.43	1	2
24C	9.18	.01	2.20	.64	.68	.14	1	4
24D	10.10	.04	3.20	.88	.77	.40	1	2
25A	9.38	.21	2.90	.91	.78	.35	1	2
25B	9.35	.23	2.70	.74	.63	.40	1	2
25C	10.70	.17	2.60	.61	.57	.54	1	6
25D	9.13	.07	3.20	1.10	.94	.27	1	3
26A	9.15	.23	3.10	.92	.84	.41	1	2
26B	7.43	.18	3.20	.71	.84	.34	1	4
26C	9.19	.27	7.40	2.20	1.12	.39	1	2
26D	9.10	.09	2.70	.59	.60	.24	1	4
26E	11.00	.19	2.90	.71	.64	.23	1	2
26F	10.70	.32	2.40	.60	.67	.36	1	6
27A	29.20	.31	14.00	3.00	.65	.43	1	2
27B	9.25	.26	7.40	2.10	1.09	.36	1	2

Lake ID	SO4 mg/l	Cl mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cu µg/l	Ni µg/l
27C	8.48	.16	2.70	.63	.67	.19	1	5
27D	8.71	.14	2.20	.54	.62	.21	1	4
28A	9.48	.28	7.30	2.20	1.13	.40	2	2
28B	7.79	.21	1.70	.43	.51	.21	3	4
28C	11.70	.22	2.90	.65	.59	.37	1	6
28D	10.40	.19	3.00	.67	.56	.35	1	4
29A	12.50	.22	5.00	.94	.88	.30	3	2
29B	6.83	.13	1.30	.33	.36	.24	2	5
29C	12.90	.22	2.80	.69	.60	.38	3	7
29D	8.42	.22	3.50	.91	.57	.40	1	2
30A	11.30	.85	2.60	.57	.61	1.20	2	5
30B	13.40	.51	2.70	.59	.59	.77	3	10
30C	13.50	.33	2.60	.57	.56	.52	3	8
30D	10.00	.16	1.50	.49	.57	.33	1	7
30E	10.20	.14	2.40	.53	.52	.18	3	13
31A	11.00	.36	3.50	.61	.62	.54	8	4
31B	10.60	.65	4.60	1.16	1.03	.90	9	2
31C	11.30	.17	3.30	.77	.73	.29	3	4
31D	10.30	.33	4.00	1.10	.96	.46	2	2
32A	11.20	.31	3.50	.51	.55	.52	7	4
32B	12.50	.33	2.80	.73	.71	.59	8	11
32C	11.50	.23	3.40	.74	.74	.44	4	4
32D	10.00	.32	2.00	.60	.68	.50	4	10
32E	10.50	.18	2.00	.66	.62	.37	3	13
33A	14.20	.77	3.90	.84	.68	1.10	8	3
33B	12.60	.24	2.20	.59	.61	.46	24	14
33C	12.60	.16	2.10	.57	.57	.39	3	15
33D	12.00	.19	2.50	.70	.61	.38	4	16
33E	10.40	.14	2.10	.64	.64	.33	4	12
34A	12.00	.22	1.50	.42	.55	.42	3	18
34B	11.50	.17	1.70	.45	.48	.36	3	15
34C	12.00	.17	2.50	.70	.62	.33	4	16
34D	10.20	.15	1.50	.39	.45	.28	6	19
34E	10.50	.14	1.30	.40	.49	.22	5	19
35A	12.00	.17	1.40	.40	.55	.32	4	23
35B	12.60	.22	2.40	.69	.63	.41	2	13
35C	12.00	.17	2.40	.72	.63	.35	4	13
35D	10.30	.27	1.20	2.60	.38	.34	5	21
36A	10.40	.09	1.20	.37	.57	.15	1	20
36B	13.10	.24	1.90	.54	.64	.44	2	24

Lake ID	SO4 mg/l	Cl mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cu µg/l	Ni µg/l
36C	13.50	.34	2.70	.75	.68	.58	5	17
36D	11.30	.13	1.80	.55	.64	.35	4	18
37A	11.00	.04	1.90	.43	.52	.29	4	23
37B	12.90	.28	2.40	.65	.60	.49	4	14
37C	12.80	.32	2.40	.62	.62	.56	4	15
37D	11.60	.23	1.10	.30	.42	.39	5	27
37E	13.10	.24	2.60	.75	.78	.57	3	17
38A	10.40	.28	1.60	.55	.51	.40	4	18
38B	12.60	.27	2.30	.65	.61	.46	4	15
38C	12.80	.26	2.30	.65	.62	.47	4	13
38D	15.20	.24	2.20	.54	.63	.52	7	34
38E	11.60	.13	4.30	.69	.71	.31	2	9
39A	11.80	.22	3.10	.72	.56	.28	3	13
39B	11.90	.24	3.40	1.03	.70	.40	4	13
39C	12.40	.89	2.80	.67	.81	1.10	11	38
39D	10.50	.17	2.40	.62	.68	.34	14	24
40A	11.10	.33	2.70	.73	.64	.49	8	16
40B	13.90	.55	5.40	1.45	.83	.80	5	7
40C	13.60	.61	7.80	2.00	1.00	.67	11	5

Lake ID	Zn µg/l	Al µg/l	Mn µg/l	Fe µg/l	Total Chlor. *a* µg/l	Corr. Chlor. *a* µg/l	Chlor. *b* µg/l	Secchi Depth m	Bottom Depth m
11A	8	260	64	55	.9	.1	.3	6.5	6.5
11B	8	290	78	67	.8	.2	.3	7.2	12.5
11C	4	40	39	14	.8	.1	.3	9.8	10.2
11D	3	31	12	26	1.4	.8	.4	4.8	15.5
11E	5	320	48	110	2.1	.7	1.1	1.7	1.7
12A	7	220	180	23	1.0	.5	.3	8.7	8.7
12B	8	430	69	50	.3	.1	.2	10.5	19.0
12C	7	470	54	110	1.9	.5	.8	1.5	1.5
12D	5	28	17	15	.8	.3	.4	5.8	5.8
13A	16	280	150	32	.4	-.2	.3	20.0	20.0
13B	10	260	140	26	.3	.1	.2	11.5	11.5
13C	11	230	130	42	.7	.1	.2	7.7	7.7
13D	7	160	110	35	.5	-.2	.2	7.0	7.0
13E	6	120	89	27	.7	.3	.4	5.2	5.2
13G	5	32	19	17	.5	.1	.3	5.8	5.8
13H	7	140	50	62	.9	-.1	.3	7.5	13.8
13I	7	210	59	54	1.1	.3	.3	7.2	12.5
14A	3	100	32	30	1.0	.5	.3	1.6	1.6
14B	6	160	100	32	.5	.1	.2	5.0	5.0
14D	7	130	72	55	1.6	.6	.3	3.9	3.9
14E	1	47	38	14	.8	.2	.3	10.0	12.0
14F	6	180	98	19	.3	.1	.1	13.5	16.5
14H	4	35	20	15	.5	.2	.3	10.5	10.5
14I	3	150	71	39	1.7	.4	.3	1.5	1.5
15A	8	380	120	23	.1	-.1	.2	15.0	20.0
15B	7	540	72	21	1.0	.4	.3	2.8	2.8
15C	1	11	6	12	1.2	.4	.6	7.6	10.4
15D	2	10	13	24	3.5	1.6	.7	4.0	7.9
16A	3	140	13	36	2.0	1.0	.5	.5	.5
16B	6	380	67	20	.8	.2	.4	2.6	2.6
16C	3	10	8	11	.7	.3	.3	10.0	12.4
16D	10	500	94	33	.5	.2	.2	9.5	11.5
17A	9	290	105	57	.2	-.1	.2	16.0	21.0
17B	7	230	82	28	1.0	.1	.3	5.3	5.3
17C	1	10	11	14	1.2	.5	.3	6.8	12.5
18A	8	570	79	61	1.3	.4	.4	1.0	1.0
18B	7	110	92	47	.4	.1	.2	11.0	15.0
18C	10	720	61	110	.8	.1	.3	4.5	6.4
18D	8	380	77	59	.4	.1	.1	4.0	4.0
18E	9	390	73	55	.7	.4	.3	6.5	18.0

Lake ID	Zn µg/l	Al µg/l	Mn µg/l	Fe µg/l	Total Chlor. *a* µg/l	Corr. Chlor. *a* µg/l	Chlor. *b* µg/l	Secchi Depth m	Bottom Depth m
19A	8	280	110	27	.4	.1	.2	5.0	5.0
19B	6	100	62	54	.9	.4	.4	6.5	7.5
19C	4	41	48	8	1.9	1.4	.3	5.0	10.6
19D	8	540	89	42	1.0	.6	.3	9.1	11.8
20A	9	400	74	41	.4	.2	.3	8.9	8.9
20B	5	350	53	100	1.2	.2	.4	3.5	13.3
20C	2	200	23	810	6.6	3.4	1.5	1.1	3.8
20D	4	150	57	25	1.3	.7	.4	7.4	7.4
21A	8	520	68	59	.3	.1	.2	11.2	11.2
21B	3	39	31	84	1.5	.5	.4	3.3	3.3
21C	4	87	54	51	.7	.2	.3	8.5	11.5
21D	6	10	60	46	2.1	.9	.4	1.3	1.3
21E	6	10	62	31	1.1	.3	.4	7.4	9.8
22A	1	27	30	56	1.4	.8	.4	2.4	2.4
22B	2	40	6	9	1.5	.9	.4	6.5	6.5
22C	3	20	35	19	1.1	.6	.4	6.8	6.8
22D	2	16	8	31	1.4	1.0	.3	7.0	14.2
22E	3	51	59	29	1.5	.6	.6	5.8	15.0
23A	6	84	60	28	1.0	.5	.3	8.3	9.3
23B	6	130	42	72	1.1	.8	.4	2.6	2.6
23C	4	15	14	35	2.3	1.4	.4	4.4	4.4
23D	6	250	34	110	2.3	.3	.5	3.6	10.5
23E	4	36	60	6	1.3	.9	.4	8.4	8.4
23F	2	55	32	94	2.5	1.5	.7	4.2	4.2
24A	4	330	27	400	1.6	.4	.6	.6	.6
24B	5	46	43	42	1.8	1.2	.3	5.9	17.3
24C	5	280	61	150	4.1	1.1	.5	2.4	8.6
24D	2	47	13	55	2.7	1.3	.6	2.0	2.0
25A	3	69	62	230	1.5	.7	.5	2.6	8.8
25B	5	75	44	93	2.0	1.0	.7	.8	.8
25C	9	200	81	18	1.1	.5	.3	8.8	20.0
25D	1	71	18	240	4.6	2.8	.8	2.0	3.9
26A	2	74	45	220	1.4	.9	.4	1.5	1.5
26B	2	140	19	340	5.0	3.3	1.4	1.2	1.9
26C	2	50	35	160	1.5	1.2	.2	1.4	1.4
26D	3	52	24	30	1.4	.9	.5	2.0	3.9
26E	2	21	27	11	1.3	.8	.4	7.8	10.9
26F	4	210	66	50	1.9	.7	.6	4.8	6.8
27A	1	13	3	13	.5	.2	.1	9.5	9.5
27B	2	44	35	160	1.1	.8	.2	3.1	4.0

Lake ID	Zn µg/l	Al µg/l	Mn µg/l	Fe µg/l	Total Chlor. *a* µg/l	Corr. Chlor. *a* µg/l	Chlor. *b* µg/l	Secchi Depth m	Bottom Depth m
27C	5	180	55	260	1.8	.4	.6	.3	.3
27D	3	120	51	100	1.6	1.0	.7	4.3	4.3
28A	3	18	30	140	1.3	.9	.2	2.9	4.8
28B	6	320	28	420	2.1	.5	.4	1.2	4.2
28C	7	110	110	30	1.4	.6	.3	6.5	10.2
28D	4	81	37	19	1.0	.4	.3	7.5	9.2
29A	5	99	13	170	2.9	2.4	.4	1.7	2.5
29B	6	190	40	260	3.7	1.7	.9	3.0	7.2
29C	10	200	180	24	.6	.3	.2	5.0	5.0
29D	1	2	7	10	1.2	.6	.2	5.8	19.0
30A	7	200	79	140	1.2	.3	.4	.3	.3
30B	10	260	220	59	.2	.1	.2	15.0	15.0
30C	9	250	220	44	.3	.1	.2	19.0	19.0
30D	6	250	50	46	3.4	2.1	.5	2.9	2.9
30E	7	130	68	58	1.3	.7	.2	5.3	10.6
31A	6	110	88	160	3.1	1.8	.8	3.4	6.5
31B	1	10	23	100	4.9	3.7	.8	4.0	6.4
31C	14	49	27	41	2.3	1.8	.5	4.8	10.7
31D	1	44	8	200	1.0	1.1	.3	4.5	12.2
32A	5	27	39	31	1.3	.8	.3	7.7	15.0
32B	9	170	140	57	.3	.1	.2	12.3	12.3
32C	4	100	38	75	1.3	.8	.4	4.8	7.5
32D	6	190	96	200	2.7	1.3	.4	4.5	7.1
32E	7	180	150	57	.8	.6	.2	4.3	4.3
33A	4	11	29	14	.7	.3	.3	8.3	11.5
33B	11	410	160	51	.3	.2	.2	18.0	21.0
33C	11	430	190	44	.3	.1	.2	12.4	12.4
33D	9	180	160	35	.3	.1	.2	9.5	13.7
33E	7	180	140	71	.8	.6	.3	2.4	2.4
34A	12	490	160	48	.3	-.1	.2	4.8	4.8
34B	12	360	200	68	.3	.2	.2	4.5	4.5
34C	8	180	160	31	.3	.1	.2	10.0	17.0
34D	9	340	110	38	.6	.4	.2	9.3	9.3
34E	10	440	130	34	.3	.2	.2	9.0	14.0
35A	12	760	160	73	.4	.4	.2	6.5	6.5
35B	9	240	150	33	.4	.1	.2	4.2	4.2
35C	8	140	150	31	.4	.1	.2	9.0	12.4
35D	13	520	220	53	.3	.1	.1	9.0	21.0
36A	10	470	73	220	.7	.3	.3	1.3	1.3
36B	15	500	140	42	.3	.1	.2	5.2	5.2

Lake ID	Zn µg/l	Al µg/l	Mn µg/l	Fe µg/l	Total Chlor. *a* µg/l	Corr. Chlor. *a* µg/l	Chlor. *b* µg/l	Secchi Depth m	Bottom Depth m
36C	8	250	130	32	.3	.1	.1	4.6	12.5
36D	8	320	130	49	.6	.3	.1	7.4	7.4
37A	10	470	67	130	2.2	1.0	.4	2.2	2.2
37B	11	300	170	34	.3	.1	.2	11.0	11.0
37C	11	300	170	43	.4	.1	.2	6.7	6.7
37D	16	770	74	110	.8	.3	.2	7.5	14.2
37E	8	150	150	46	.2	.1	.1	11.2	11.2
38A	9	180	130	44	.6	.2	.2	3.7	3.7
38B	10	280	170	53	.4	.3	.2	3.1	3.1
38C	11	280	160	42	.3	.2	.1	6.8	6.8
38D	14	520	290	64	.3	.1	.2	10.5	11.0
38E	2	34	49	92	2.3	.9	.8	1.8	1.8
39A	8	120	130	130	1.1	.6	.4	.6	.6
39B	6	25	52	88	2.0	1.4	.4	4.8	12.2
39C	14	270	120	75	.5	.3	.2	2.4	2.4
39D	9	250	130	260	2.2	1.1	.5	3.4	18.0
40A	10	180	130	64	1.6	1.2	.3	3.7	3.7
40B	2	16	16	54	1.9	1.3	.3	3.6	6.1
40C	1	13	6	43	1.0	.9	.3	3.7	4.2